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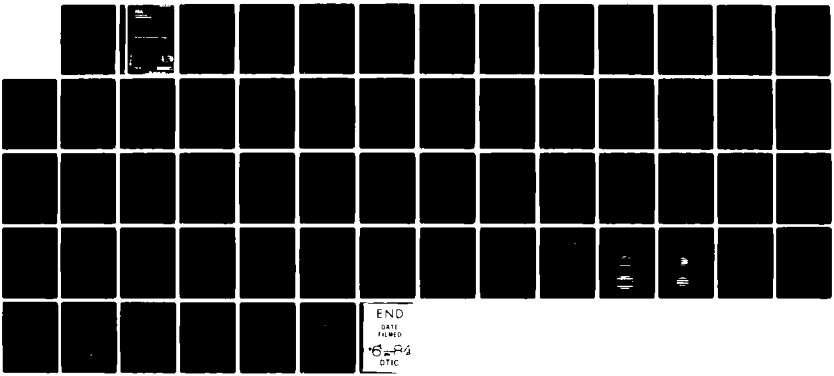

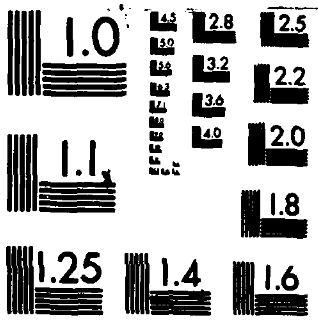

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The Aeronautical Research Institute of Sweden

Memorandum 121

STUDIES OF CONTAMINATED RUNWAYS

by

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SUMMARY

The report describes the friction forces acting in the tyre-ground contact area during braking and how these forces are influenced by different parameters. It appears possible to avoid most cases of water- and slush-planing by constructing the runways with a harsh microstructure and an open coarse macrostructure.

The report contains comparative measurements between aircraft and brake number measuring vehicles equipped with different types of tyres. These measurements were mostly done during winter conditions. On runways with attached dry deposits, also compacted snow and ice at low temperature, the results show that current vehicles measure brake numbers representative of aircraft, even if large differences in parameter values between the vehicles and the aircraft exist.

On attached dry deposits the brake number of a tyre is not seriously dependent of speed, inflation pressure, etc. On loose contaminations such as water, slush or wet snow on the contrary the brake numbers are speed dependent and are also influenced by the tyre inflation pressure, the geometry of the footprint and its deflection, the combined tyre runway drainage capability, etc. From the results it appears possible to get a reasonable correlation also in the latter case if such parameters as speed, inflation pressure, slip ratio are relatively equal in both the measuring tyre and the aircraft tyres.

A specification of a new measuring tyre with characteristics similar to aircraft tyres, and which is adopted as standard in Sweden is included.

Stockholm, August 1980

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1. INTRODUCTION

The friction forces between the aircraft's tyres and the runway are the primary means for stopping the aircraft on landing or at aborted take-off. Engine reverse thrust is only considered as a complement, although it contributes a great deal to braking action during slippery runway conditions.

Clean and dry runways do not cause any braking difficulties, but contaminations in the form of snow, ice, slush or water limit the available friction. During unfavourable conditions the minimum braking length necessary can be several times the certified landing one. Low friction between tyre and runway also limits the yaw control of an aircraft rolling along a runway and hence the permitted crosswind.

To the pilot, a slippery runway implies that, when approaching an airport, he must receive an up-to-date and correct report of measured braking action and meteorological conditions in order to determine whether a landing is possible or not with regard to existing safety regulations.

Many airports in Sweden, Norway, Denmark and Finland have brake number measuring vehicles of type Apeco BV-11 or Saab Friction Tester to be able to give to the pilots information of current friction conditions.

For certain types of runway contamination and especially at temperatures around 0°C it happens that the pilots experience a different, often poorer, braking action from that recorded by the measuring vehicle. Usually this is not due to incorrect measurements but because of the inability of the measuring vehicle to simulate correctly braking action of an aircraft wheel.

In order to investigate these conditions, a study of braking action during landing on contaminated runways was started at FFA in autumn of 1972 on the initiative of STU (Swedish Board for Technical Development) and was finished in spring of 1979. The present report, which has been compiled at the request of the Swedish Board of Civil Aviation, is based on the work mentioned, ref. [1], and on the available international literature.

2. SYMBOLS

A	footprint area	m^2
A_1	footprint area with dynamic planing	m^2
A_2	footprint area with viscous planing	m^2
A_3	footprint area with dry friction	m^2
B	footprint width	m
L	footprint length	m
F	friction force	N
F_s	slide friction force	N

F_a	adhesion friction force	N
F_h	hysteresis friction force	N
F_F	fluid drag	N
F_{Fp}	fluid drag at complete dynamic planing	N
F_R	rolling resistance force	N
Z	vertical force	N
X	horizontal force	N
N	normal force	N
T	brake torque	Nm
H	water depth	m
H'	see definition in connection with (14)	m
S	slip ratio	
S_D	slip ratio due to horizontal footprint deformation	
S_S	slip ratio due to horizontal footprint sliding	
R	mean runway texture depth	m
V	peripheral speed equivalent with ω	m/s
V_R	peripheral speed equivalent with ω_R	m/s
V_G	ground speed	m/s
V_p	dynamic planing speed	m/s
V_{pmin}	dynamic planing speed at a water depth > critical	m/s
V_{sp}	dynamic slush planing speed	m/s
ΔV	peripheral speed difference	m/s
ΔV_D	deformation speed	m/s
ΔV_S	sliding speed	m/s
S_e	corrected brake distance	m
S'_e	certified brake distance	m
a	aircraft acceleration	m/s^2
f	brake number	
f_w	brake number in wet	
f_{d0}	brake number in dry and at $V_G \sim 0$	
f_F	fluid brake number	
f_R	rolling resistance number	
f_S	slide brake number	
f_a	adhesion brake number	
f_h	hysteresis brake number	
f_p	pilot determined brake number	
d	tyre vertical deflection	m
r	tyre radius, loaded	m
e	centre of pressure of footprint	m

g	gravity	m/s^2
p	tyre inflation pressure	Pa
p_G	stagnation pressure	Pa
ω	wheel angular speed in braked rolling	rad/s
ω_R	wheel angular speed in unbraked rolling	rad/s
ρ	density of water	kg/m^3
ρ_s	density of slush	kg/m^3

3. FORCES BETWEEN A TYRE AND A DRY RUNWAY

3.1. Rolling resistance

When a standing pneumatic tyre on a runway is exposed to a vertical force, the tyre deflects according to figure 1. A "footprint" is formed with a distributed pressure, which resultant is a vertical force through the centre of the wheel. The local pressure is influenced by the stiffness distribution of the carcass and the inflation pressure. The latter also influences the footprint area strongly. Because of the deflection of the tyre also local horizontal forces are present. As long as the tyre is standing the resultant to these forces is zero.

The side walls of an aircraft tyre are flexible and carry only a fraction of the vertical load. It is consequently possible to write

$$N = p \cdot A \tag{1}$$

without an error larger than a few per cent (see e.g. [2]). Is the tyre treaded, A refers to the incribed area.

When the tyre is rolling the pressure distribution in the footprint is changed due to the visco-elastic properties of the rubber, and the resultant vertical force moves in front of the centre of the wheel and opposes the rotation. If the free rolling is maintained due to a towing force in the wheel centre, an equivalent resultant horizontal force forms in the footprint. This force, which causes a deflection of the tread in the direction of the movement, is designated the rolling friction force of the wheel. According to figure 2 its size is

$$F_R = N \cdot \frac{e}{r} \tag{2}$$

Due to the rotation of the wheel e and r increase slightly with speed.

In practice F_R also contains contributions from bearing friction, dragging brakes and the deflection of the runway.

By defining a brake number as

$$f = \frac{F}{N} \tag{3}$$

(2) may be written as

$$f_R = \frac{e}{r} \tag{4}$$

Due to the peripheral deflection of the tyre in the footprint the rotational speed of the wheel will be a little smaller than the theoretical speed when rolling free (no rolling resistance). With constant vertical load the rolling resistance is reduced, when the inflation pressure is increased. It is also reduced slightly with increased temperature. Normally the rolling resistance coefficient or brake number is small ($f_R < 0.1$).

3.2. Slide friction

If the peripheral speed of the footprint is less than the horizontal speed of the centre of the wheel, due to braking of the wheel, the tread is deflected horizontally in the footprint and its nearest surroundings due to friction forces between the tyre and the runway. When the deflection reaches a certain limit also sliding occurs in the footprint. To define the relative motion between the tread and the runway one uses the concept of slip ratio, which is by definition (see e.g. [3] page 5).

$$S = 1 - \frac{\omega}{\omega_R} \tag{5}$$

With $V = \omega . r$ and $V_R = \omega_R \cdot r$ it is possible to write

$$S = 1 - \frac{V}{V_R} = \frac{\Delta V}{V_R} \tag{6}$$

$S = 0$ is equivalent to a theoretically free rolling wheel
$S = 1$ is equivalent to a locked wheel without rotation.

If the speed difference ΔV is parted in

$$\Delta V = \Delta V_D + \Delta V_S \tag{7}$$

in principle the relations in figure 3 are obtained. It is also possible to introduce corresponding slip ratio definitions, which may be written

$$S = S_D + S_S \tag{8}$$

with $S_D = \frac{\Delta V_D}{V_R}$ and $S_S = \frac{\Delta V_S}{V_R}$

By slide friction we refer to the friction which is produced due to the relative motion between a rubber tyre and a hard runway. This type of friction is due to the adhesion between the surfaces in the footprint and the hysteresis in the tyre tread.

The slide-friction may be written

$$F_S = F_a + F_h \tag{9}$$

and the slide-brake number on a dry runway may by definition be expressed as

$$f_S = \frac{F_S}{N} = \frac{F_a}{N} + \frac{F_h}{N}$$

or

$$f_S = f_a + f_h \tag{10}$$

The description below is based on [4] and [5], which in a detailed way describe the phenomenon.

3.2.1. Adhesion friction

Figure 4 shows brake number vs. sliding speed, when a rubber block slides along a hard smooth surface. In the interface, forces (adhesion) arise between the molecules of the two materials. These forces are time dependent due to the sliding speed. The value of the resultant horizontal component of these forces depends primarily on the closeness of the surfaces, the size of the surfaces and on the sliding speed. The rubber compound, the temperature and the texture of the surfaces also have influence. Due to the viscoelastic properties of rubber, which mean that the force and the deflection are out of phase, it is possible to use the resultant horizontal force-component for braking purposes.

The adhesion losses increase with sliding speed up to a maximum and then decrease. The value of the sliding speed for maximum adhesion losses is very small, only about 5 cm/s, and it increases slightly with temperature.

The adhesion only concerns the surface of the tread and it decreases very fast if the interface surfaces are separated. It ceases totally if the separation exceeds fractions of a micrometer. The adhesion losses depend on the number of simultaneous molecular bonds and may consequently be independent of the normal force between the surfaces

and only dependent of the size of the interface. This is contradictory to the classical theory of friction for rigid bodies. In spite of this it is possible to use the classical expression.

$$F = f \cdot N \tag{11}$$

and the reasons may be illustrated in the following way.

a) If the inflation pressure of a tyre is constant and the vertical load varies, the apparent interface will be proportional to the load. The adhesion losses are consequently proportional to the load.

b) If the load on a tyre is constant and the inflation pressure varies, the size of the apparent interface will change inversely proportional to the pressure. Experimentally it is known that the adhesion losses are not changed inversely proportional to the inflation pressure, but considerably less. This depends on the fact that only a part of the apparent surfaces are in contact with each other and that the real contact surface due to the elasticity of the rubber increases proportionally to the inflation pressure (the specific normal force). See e.g. [2].

The condition that only a part of the apparent surfaces are in contact with each other may be illustrated by the fact that the dry friction number between an aircraft tyre and a runway very seldom exceeds 0.9 and that it is possible to measure friction numbers of > 4 on carefully prepared surfaces (also on dry ice) in the laboratory.

The adhesion losses are also influenced by the rubber compound. Mixtures of natural rubber produce lower losses than synthetic rubber mixtures at room temperature. The contrary is true when the temperature is below the freezing point.

The adhesion losses are often referred to as the microcharacteristic of the friction.

3.2.2. Hysteresis friction

The hysteresis losses depend on the deformation of the rubber, when the tread slides across the roughness of the runway. The resulting horizontal force is also here a consequence of the viscoelastic quality of the rubber. The friction number increases with sliding speed (see figure 4) and the maximum is shifted to higher speed when the temperature increases. However, the maximum value occurs at such a high sliding speed that it is not possible in practice to take advantage of it. The process which produces hysteresis losses takes place in the whole part of the tread, which is affected by the roughness of the runway, and consequently involves a larger tread volume than the adhesion loss process does. It is obvious that it is impossible to produce hysteresis losses

if the runway has no macrotexture. The hysteresis losses are not influenced, when the surfaces in the interface are slightly separated.

a) The hysteresis losses will be proportional to the normal load by the same reason as was mentioned earlier for adhesion losses, when the inflation pressure is constant and the load varies.

b) The contact surface of the active volume of the tread decreases inversely proportional to the inflation pressure when the vertical load is constant and the inflation pressure varies. The hysteresis losses will be constant if the height of the active volume is proportional to the inflation pressure (specific load). The literature does not include any information about this matter.

The hysteresis losses are often referred to as the macrocharacteristic of the friction.

4. FORCES BETWEEN A TYRE AND A RUNWAY WITH LOOSE CONTAMINATIONS

4.1. Hydrodynamic resistance

When a wheel is rolling unbraked along a runway contaminated with water, slush or loose snow, most of it will be displaced by the wheel. This causes a drag equivalent to the component of the impulse the wheel is transmitted in the direction of the movement to the loose matter on the runway. The contaminating layer is normally thin, and it is permitted to consider the drag to be positioned along the footprint. A fluid brake number may be defined as

$$f_F = \frac{F_F}{N} \tag{12}$$

Figure 5 shows an example of fluid drag vs. speed taken from [6]. The extreme value is equivalent to fully developed dynamic hydroplaning. The variation of drag with speed reflects the change of the flow when the wheel is gradually planing. If the spray of water. slush or snow hits the structure of the aircraft additional drag is caused, which may reach to 1 or 2 times the F_F.

4.2. Water contaminated runway

When a runway is contaminated with water the friction is changed considerably compared with dry conditions. The adhesion between the runway and the tyre disappears when the footprint surfaces are separated by the water layer. The shear-forces, due to the motion of the wheel in the water-layer, are furthermore too small to have any influence on the braking capability of the wheel.

The tyre must displace the water and cause dry contact at least with parts of the runway to produce friction. The possible amount of

friction depends on the size of the dry surface in relation to the total footprint. The flow field in front of and below a rolling or a skidding wheel is very complicated and is influenced by many parameters. To simplify the picture and to reduce the simultaneous influence of the parameters involved the concepts of "viscous" and "dynamic" hydroplaning have been introduced in the literature. By definition there are distinct differences between these two types of planing. In reality the flow within the water layer changes, when the footprint passes it. The flow picture is gradually modified from what we call dynamic to what we call viscous planing.

Is the water-layer sufficiently deep, a dynamic pressure is formed in it immediately in front of the footprint of the tyre. The water-layer is partly catched by the footprint and gradually pressed away from it, primarily sideways by the local pressure between the tyre and the runway.

4.2.1. Viscous hydroplaning

On more or less smooth and closed textured runways viscous hydroplaning occurs. It is characterized by the inability of the rolling or skidding tyre to remove the last thin layer of water in the footprint. This type of planing may occur even if the contaminating water layer is very thin. The local pressure caused by the tyre is trying to displace the water, and the inertia and viscosity of the water are opposing the process. The available time to remove the layer depends on the length of the footprint and on the speed of the wheel. The necessary time to remove the layer depends on the amount of water which must be removed and on the distance the water must be displaced. The micro- and macrostructure of the runway and the tread are of paramount importance in this respect. Information in [7] indicates that pure viscous planing only occurs on very smooth and finetextured surfaces and that a macrotexture depth of only ~ 0.3 mm is sufficient to prevent such planing.

Viscous planing complete or partial may proceed down to very low speed on polished surfaces. Measurements published in [8] indicate, that the pressure in the footprint layer of a rolling tyre on a smooth surface with no macrotexture may be written

$$\frac{p_G}{p} = 0.17 \cdot \frac{V_G}{V_p} + 0.83 \qquad (13)$$

within the speed range of $0.3 < \frac{V_G}{V_p}$.

V_p is here determined from

$$V_p = 0.054\sqrt{p}$$

which is Horne's equation for dynamic planing in SI-units.

Viscous planing prevents adhesion forces to form in the footprint The separating water-layer needs only to be a few molecules thick.

The flow in the tyre-ground contact area is also influenced by the sliding speed between the tread and the runway. However, the literature does not include any information, which illustrates the difference in drainage capability between a rolling and a sliding tyre exposed to viscous planing.

The rotation of a wheel exposed to total viscous planing ceases gradually. This depends on the absence of any horizontal force in the footprint, which can balance the moment due to the verical force in the tyre-ground contact area.

4.2.2. Dynamic hydroplaning

If bulk water is present, it is necessary for the tyre to displace it in a forward direction and to the sides. In front of the footprint, where the water hits the tyre, a pressure is formed corresponding to the impulse, which is transmitted from the tyre. This pressure, which is proportional to the speed of the wheel squared and the density of the water, deflects the tyre in such a way that the water successively is able to penetrate the tyre-ground contact area and partly carry the vertical load of the wheel. At a certain water depth or larger and at a characteristic speed no contact exists any longer between the tyre and the runway. The tyre is exposed to complete dynamic planing and no adhesion and only small hysteresis losses are present in the footprint.

The flow around and beneath the wheel changes considerably with speed. At low speeds the tyre behaves as a displacing object and with increasing speed it starts to plane on the water surface. The spray pattern around the tyre is primarily voluminous and directed both forward and at the sides. When planing is dominating the forward spray practically disappears and the spray at the sides is concentrated and intensified.

An increase of the water depth above its critical value does not influence the planing speed appreciably. A decrease of the water depth below its critical value increases the necessary speed for complete planing with a factor inversely proportional to a factor containing the water depth. In [9] the following equation is presented

$$V_p = V_{pmin} - k + \frac{m}{H-H^1} \tag{14}$$

where H = the water depth and H^1 = the water depth giving $V_p = \infty$. k and m are coefficients, which depends on inflation pressure.

Complete dynamic hydroplaning cannot occur below a certain water depth on a runway provided with a macrostructure.

Consider a tyre with a smooth tread rolling on a smooth and closed textured runway contaminated with a water layer equivalent to or deeper than the critical value. Experimentally it is shown in [6] that complete dynamic aquaplaning occurs at a speed equivalent to

$$V_p = 0.054 \sqrt{p}$$

$$\text{or} = 1.7 \sqrt{p} \text{ with p in kPa} \qquad (15)$$

If the tyre is sliding instead of rolling the relationships will be

$$V_p = 0.046 \sqrt{p}$$

$$\text{or} = 1.5 \sqrt{p} \text{ with p in kPa} \qquad (16)$$

When the depth of the water layer is smaller than its critical value the conditions are more complicated and the planing speed is influenced by the tyre geometry. This is shown by the following theoretical equation from [7]

$$V_p = 0.11 \cdot \frac{L}{B} \sqrt{p} \cdot \frac{1}{\ln\left[1 + \frac{H}{R} + \sqrt{\frac{H}{R}\left(2 + \frac{H}{R}\right)}\right]} \qquad (17)$$

(17) is only valid when a smooth tyre rolls along a textured runway and when L > B, say 2B. The same reference also includes an equation valid for tyres with longitudinal grooves and valid for water depth smaller than the depth of the grooves.

It is obvious that recalculating the planing speed between inflation pressures is a complicated problem with no simple solution when the water depth is smaller than its critical value.

The pressure in the stagnation area in front of the tyre may be written.

$$\frac{p_G}{p} = \left(\frac{V_G}{V_p}\right)^2 \qquad (18)$$

If the runway is provided with a macrostructure and the tread is patterned the necessary water layer for complete dynamic planing is deeper than if the runway and the tread are smooth. From a drainage point of view the macrotexture is more important than the grooves in the tread.

A rotating wheel which is exposed to planing stops its rotation gradually and may also rotate backwards. The moment from the vertical force in the footprint counteracts the rotation and no horizontal force in the footprint exists which can balance this effect.

4.2.3. Reverted rubber planing

If the aircraft when touching down is exposed to complete dynamic planing no spin-up occurs. This happens if the water layer is deep enough and the touch-down speed is above the hydroplaning speed of the aircraft. Due to the macrostructure of the runway, the rubber in the non-rotating footprint will be subjected to repeated local deformations, which due to the visco elastic properties of the rubber will produce heat in the footprint. If this process continues the temperature in the footprint may reach the level when the rubber loses its elastic quality and becomes practically plastic.

When this happens a large part of the hysteresis losses disappear and if the runway is smooth and fine-textured also viscous planing will continue down to low speed. Due to the softness of the rubber the adhesion losses will be small and the wheels will spin-up very late, far below the speed at which dynamic planing ceases.

The process is called "reverted rubber planing" and a tyre exposed to such a process shows damages in form of a local sticky surface or a locally worn-off layer. The steam, which sometimes is possible to notice around the wheel, nowaday is regarded [10] to be a consequence of the process and not a reason for it, which has been stated earlier in the literature.

4.3. Slush contaminated runway

Slush is a mixture of water and snow. The temperature is zero or a little above the freezing point. Slush behaves as a liquid in the sense that only insignificant shear-forces may be transmitted. The density of slush depends on its water content and it is always less than the density of water. The viscosity of slush is always larger than that of water and it increases with decreasing water content.

Viscous slush planing occurs in the same way as viscous water planing. The larger viscosity means that such planing may occur on runways with closed macrostructure even if the microstructure is fairly harsh.

Dynamic slush planing happens in the same way as dynamic water planing, but at a higher speed. The difference may be expressed with

$$V_{sp} - V_p = V_p\left(\sqrt{\frac{\rho}{\rho_s}} - 1\right) \qquad (19)$$

The relative density of slush may be in the bracket 0.5 to 0.8 depending on the water content.

4.4. Snow contaminated runway

To distinguish between slush and wet snow is a question of definition. The temperature must be around the freezing point and the density increases with the water content. Newly fallen wet snow also contains a lot of air. Wet snow is compacted by a rolling wheel and forms a layer, which prevents the tyre to come in contact with the microtexture of the runway. The friction conditions will largely be the same as for viscous planing on a smooth and closed surface.

If the snow is already compacted and the temperature decreases the water in the snow will freeze and a hard surface form. In case the surface stays dry, adhesion losses may be produced by a tyre. However, due to the heat produced through the compression of the snow and the rolling resistance of the tyre a water film may be produced, which eliminates the adhesion losses.

When the snow, in front of the wheel, is loose and dry most of it will be blown away by the wheel, and the runway will be more or less clean. A fraction of the snow may, however, be catched and compacted between the tread and the runway and mask the microstructure.

4.5. Ice contaminated runway

When a water covered runway is freezing the ice will mask the structure more or less and produce a closed surface. Adhesion losses may be produced on such a surface as long as the surface is dry. If water is produced in the interface due to the movement of the wheel the adhesion losses will cease.

Independent of the macrotexture a harsh microtexture may be masked by hoar frost.

Water may be produced due to heat accumulated in the tyre or heat produced by the rolling resistance when the speed of the wheel is reduced below a certain value. The result will be a reduction in the adhesion losses when the speed slows down.

4.6. Mixed hydroplaning model

Total viscous or dynamic hydroplaning are exceptional cases. The normal is a simultaneous existance within the footprint of a dry area, an area with viscous planing and one with dynamic planing. This is shown in figure 6 from [11].

Disregarding the rolling and the fluid resistance, the brake number of the tyre may be expressed by

$$f_w = \frac{(A_1+A_2)\ f_h + A_3(f_a+f_h)}{A} \tag{20}$$

if the local pressure in the footprint is represented by the inflation pressure. The equation expresses that only that part of the footprint which is in dry contact with the runway contributes essentially to the braking capability of the tyre. The footprint area, which becomes separated from the ground by a layer of water, may only produce hysteresis losses, more or less depending on the thickness of the water-layer.

If the wheel is stationary dry friction may be available from the whole surface $A_3 = A$. If the microstructure of the runway is smooth and the wheel starts to roll a surface A_2 with viscous planing will progressively be formed. This surface develops backwards with increasing speed and reduces the dry friction area A_3. Due to the speed a dynamic pressure will develop in front of the wheel if bulk water is present, which gradually will penetrate the footprint. An area with dynamic planing A_1 and which intrudes on the area A_2 is formed. When the speed increases further, the area A_3 will gradually disappear and at the same time A_1 will be larger. At a certain critical speed and if the water depth is large enough the area A_1 will cover the whole footprint and the tyre is exposed to complete dynamic planing.

On a harsh microstructure the area A_2 will never develop and the area A_1 will gradually replace A_3. The speed for complete dynamic planing will be the same if the water depth is $\geq$ its critical value.

W.B. Horne at NASA presented in the beginning of 1978 a combined viscous-dynamic hydroplaning theory, where he uses the 3-zone concept according to (20), but with $f_h = 0$. Together with empirically obtained values of the local pressure between a tyre and a smooth wet runway he designed an analytical model for prediction of brake numbers vs. speed on differently textured runways. The theory seems to be a tool, which together with properly done brake number measurements can map the friction quality of a wet runway. If so it should be possible to give daily information to pilots about the brake number vs. speed with the help of separate brake number measurements or rain-intensity measurements. It is not possible to give a reference to the theory because to the knowledge of the authors it is not yet officially published by NASA.

5. FRICTION CHARACTERISTICS OF TYPICAL RUNWAYS

5.1. Characterization of the surface structure of a runway

The concepts of microstructure and macrostructure are used to characterize the friction and drainage qualities of a runway.

The microstructure, which refers to the texture of the individual stones in the pavement, may be smooth or harsh. A smooth texture causes large adhesion losses in dry condition. It permits close contact within the interface and consequently many molecular bonds. In wet on the contrary a smooth texture causes small adhesion losses because of the difficulty to remove the final thin layer of water

in the footprint. A layer of dust particularly if damp has the same effect. It is not possible to get viscous hydroplaning without a smooth microtexture.

A harsh, dry microstructure causes slightly lower adhesion losses than a smooth dry texture, because the real contact area within the interface will be smaller. In wet a harsh texture still causes dry contact in a large part of the interface due to the sharp asperities which break through the thin water layer. The harshness also permits a more efficient drainage of the water due to the channels, which are formed in the interface. A harsh microstructure prevents viscous hydroplaning, but not necessarily viscous slush-planing.

The macrostructure, which depends on the sizes and relative quantities of the aggregates, may be closed (fine) or open (coarse). The irregularities are small compared with the length of the footprint of a tyre but large compared with the microtexture. A closed or fine textured surface means small hysteresis losses because the energy dissipation due to the repeated local deformation in the tread is small. An open or coarse textured surface causes on the contrary large hysteresis losses.

When the water layer is sufficiently deep (critical depth) and the speed sufficiently high (critical speed) total dynamic hydroplaning occurs because the water lifts the wheel and prevents contact between the ground and the tyre. If the water-depth decreases below its critical value complete dynamic planing may still happen but at a higher speed. The value of the critical depth depends on the macrostructure, and it needs to be larger on a coarse than on a fine structure. This depends on the channels, which are formed between the tread and the runway in the interface and which improve the drainage of the interface. It is possible to prevent dynamic hydroplaning at reasonable rain intensities by choosing a sufficiently coarse macrostructure. The planing speed on such a structure will be higher than the touch-down speeds of heavy aircraft. Grooving of a runway may be equivalent with coarse macrostructure if the grooves are positioned close enough.

Rubber deposits and paintings mask primarily the microstructure of a runway.

5.2. Runway with smooth microstructure and closed macrostructure

A runway with a smooth microstructure and a closed macrostructure causes when dry together with a rubber tyre brake numbers from ~ 0.7 to 1.1 depending on the rubber mixture and inflation pressure. On this type of runway the adhesion losses completely dominate the situation. The brake number decreases slightly with increasing inflation pressure and temperature. The reason why the brake number in practice does not exceed the numbers indicated despite a smooth surface, is that the real ground-tyre contact area is much smaller than the apparent area represented by the interface. It is only the real contact area which can produce adhesion losses. As was mentioned

earlier it is possible to measure friction numbers of > 4 on a dry ice surface during well controlled laboratory conditions.

The available friction on a dry and clean runway with these types of structures is independent of the speed of the wheel. The maximum value of the brake number occurs at a sliding speed of ~ 0.05 m/s. If the sum of this speed and the longitudinal deformation speed of the tyre in the footprint is converted into wheel slip ratio a figure of 10 to 15% will appear. In comparison with the deformation speed the optimum sliding speed is very small and it is reasonable to consider the optimum slip ratio to be independent of wheel speed.

A runway with smooth microstructure and closed macrostructure, which is damp or wet, causes very low brake numbers down to low speed due to viscous hydroplaning. A very thin layer of water between the tread and the runway eliminates the adhesion losses. It is not possible for the tyre to press away the water completely in the footprint during the time available. Due to the time dependence of the water removal process, the brake number will decrease with increasing speed.

When the runway is flooded the viscous planing will continuously be replaced by dynamic planing when the speed increases. The absence of macrostructure means that the critical water depth for complete dynamic planing is relatively small. On this type of runways the tread pattern is very important in limiting both viscous and dynamic planing.

If the water layer is sufficiently deep, no spin-up of the wheels will occur at touch-down. The planing with non-rotating wheels which follows becomes very extended on this type of runway and ends up as a reverted rubber planing. The absence of macrostructure means in principle that no reverting of the rubber should happen. The literature contains no information about the smallest macrostructure necessary to produce such planing.

Slush and wet snow aggravate the situation further and cause viscous planing down to very low speed. The brake number becomes practically zero within the whole speed range, if the runway is covered with ice or hoar frost and the temperature is around the freezing point. Relatively high brake numbers are obtained if the ice is dry. In practice this can only happen at low temperatures.

The situation will not be worse by rubber deposits. Loose sand on a runway of this type is ineffective. Dust and mud together with small amounts of water produce a very slippery surface.

On this type of runway the available brake number in wet is very speed dependent. The friction is of adhesion type and its maximum value occurs at the same sliding speed as when the runway is dry. However, the optimum slip-value is considerably lower, perhaps only 5 to 10%.

Figure 7a shows in principle in dry and wet the brake number vs. speed, when a tyre is braked on a runway with smooth micro- and

closed macrostructure. In practice no runway has such extreme characteristics, and the dotted curve is more likely.

5.3. Runway with harsh microstructure and closed macrostructure

A runway with harsh microstructure and closed macrostructure causes when dry together with a rubber tyre slightly smaller brake numbers than a smooth microstructure. The friction losses depend on adhesion and in practice the reduction mentioned is unimportant. In wet the harsh microstructure prevents viscous planing. The asperities break through the water layer locally in many points and make possible adhesion losses in the dry points. The harsh microstructure cannot influence the forming of dynamic planing if the runway is flooded and probably not prevent reverted rubber planing if the wheels have been non-rotating since touch-down. On a closed macrostructure a tread pattern counteracts dynamic planing.

The harsh microstructure can only partly prevent viscous planing on runways contaminated with slush or wet snow. Ice or hoar frost may mask the microstructure and cause the runway to behave as a runway with smooth microstructure.

Rubber deposits and painting mask the microstructure. Loose sand does not give such low friction as on smooth microstructure. Dust and mud together with a light rain do not destroy the possibility to get adhesion losses.

Figure 7b shows in principle brake number vs. speed in dry and wet. If the dynamic planing becomes partial or total depends on the water depth.

5.4. Runway with smooth microstructure and open macrostructure

A runway with smooth microstructure and open macrostructure causes when dry together with a rubber tyre brake numbers which are comparable with case 5.2. They are probably slightly smaller if the open macrostructure is very coarse. The adhesion losses dominate the situation, but the hysteresis losses due to the macrostructure may be up to 25% of the brake number value.

The smooth microstructure means that viscous planing would be possible down to low speeds, however, not as low speeds as if the open macrostructure was missing. The hysteresis part of the friction losses is not influenced by the presence of a thin layer of water.

When flooded the flow conditions in the interface differ considerably between coarse and fine macrostructure. The water partly passes through the channels which are formed between the tread and the coarse runway. As a consequence the necessary water depth for complete dynamic planing must be larger than for a fine textured macrostructure. However, the planing speed is only influenced if the water depth is smaller than its critical value. The necessary "critical" water depth increases with the coarseness of the macro-

structure. For a given rain intensity it is possible to choose a macrostructure, which eliminates the possibility of dynamic planing. Some viscous planing may, however, remain due to the smooth microstructure.

This type of runway causes viscous planing when contaminated with slush and wet snow. However, the coarse macrostructure means that some hysteresis losses probably remain. If the runway is covered with a thin layer of ice or hoar frost and the temperature is around zero degrees the brake number will be low within the whole speed range. At low temperatures when the ice remains dry relatively large brake numbers may be obtainable.

The friction qualities of this type of runway are, in principle, not influenced by rubber deposits or loose sand. Dust and mud together with light rain will produce viscous planing. However, the hysteresis losses remain.

Figure 7c illustrates in principle the brake number vs. speed. Normally a runway has a semiharsh microstructure, which means that the brake number below $V_G/V_p = 1$ will follow a curve above the indicated curve, e.g. the dotted curve.

5.5. Runway with harsh microstructure and open macrostructure

In dry conditions a runway with harsh microstructure and coarse (open) macrostructure causes brake numbers slightly below what is possible with smooth microstructure. The adhesion losses dominate, but the contribution of hysteresis losses from the macrostructure may be as high as 25% of the brake numbers.

The harsh microstructure prevents forming of viscous planing when the runway is damp or wet. The coarse macrostructure prevents dynamic planing if the water depth is not to large, see 5.4.

On this type of runway the risk of viscous planing caused by slush and wet snow is smaller than on the other types of runways mentioned. To produce viscous planing the snow must be compacted and mask the whole macrostructure. Thin ice and hoar frost may mask the microstructure and prevent adhesion losses. However, the hysteresis losses remain.

Rubber deposits may mask the microstructure. Loose sand will probably not influence the brake number. Dust and mud with a light rain do not eliminate the adhesion losses.

Figure 7d shows in principle the brake number vs. speed in dry and in wet. The curve in wet illustrates the case when the macrostructure is coarse enough to prevent total dynamic planing. This type of runway is the most preferable when the problem is to suppress the possibilities of viscous and dynamic planing.

6. PILOTS' REPORT INVESTIGATION

The purpose of the pilots' report investigation was to try to obtain a picture of why and how often the brake number reported to the pilot does not coincide with the brake number experienced by the pilot on landing. The investigation, which was effected during the winter seasons 1972-76, has earlier been described in [12], where also the results from 1972-75 are presented in detail.

Figure 8 represents the statistical results from the complete investigation. The bars express in per cent the number of cases, when the pilot considers the aircraft to have experienced a lower brake number ($\Delta f > 0.05$) than that reported to him. His judgement was based on the braking distance used. The basis for the calculation of the different percentages is the number of cases, when the pilots asked for brake number information or considered it motivated to report estimated brake value to the tower. The majority of and the greatest differences were observed during the following conditions.

1. Runways with smooth (polished) microstructure and closed (fine) macrostructure. When such runways are covered with loose contaminations the brake numbers become very speed dependent.

2. Runway temperatures around 0°C. If the contamination is ice or hoar frost a water film may form due to the heat in the tyre. If snow is present the compression energy which the tyre exerts may produce a water film. A water film is sufficient to eliminate the adhesion losses if the microstructure of the runway is masked.

3. Runways with small or negative transverse slope. Poor drainage contributes to water or slush planing if the runway structure is unsuitable. The available brake numbers will be very speed dependent.

4. Contaminations such as water, slush, or a mixture of dust, mud and light rain.

5. When meteorological changes have occurred between the time of vehicle measurement and landing aircraft.

6. Runways with many slippery spots (paintings, rubber deposits, oil or fuel spillages, ice, water). The efficiency of present types of anti-skid systems on aircraft drops when many slippery spots are present.

7. Short runways with poor visibility.

8. Urea treatment at too low temperature and ureaslush remainders.

The results mentioned show that a large part of the differences reported concern cases when the brake number is speed dependent. The speed of the measuring vehicle was earlier 65 km/h and it is not surprising to find that such measurements correlate poorly with the braking capabilities of landing aircraft when the available brake numbers are speed dependent.

7. CHARACTERISTIC DIFFERENCES BETWEEN MEASURING VEHICLES AND AIRCRAFT

7.1. Parameters

Table 1 shows some characteristic differences between the trailer BV-11 and the aircraft used in the investigation.

The difference in inflation pressure means that the wheels have different dynamic water or slush planing speeds. Owing to differences in the footprint geometry it is not possible to use directly equation (15) for recalculations of fully developed dynamic planing speeds. The critical waterdepth is dependent on both the length of the footprint and on the length of the drainage path. It is possible that different inflation pressure also influences the onset of viscous-planing. The literature lacks information on this subject. Figures 9 and 10 show dynamic waterplaning tests at different inflation pressures with an early version of the measuring tyre Aero with 6 ribs. This tyre is equivalent to the original BV-11 tyre except for the tread pattern. At low inflation pressure (figure 9) the deflected footprint is quite different from the corresponding footprint of a planing aircraft tyre. This depends on the fact that the relative stiffness of the side walls of the tyre in relation to the stiffness caused by the inflation pressure increases with decreasing pressure. At high inflation pressure (figure 10) the deflected footprint is similar to that of an aircraft tyre.

The difference in wheel diameter is primarily of minor importance. However, at the same relative deflection this means different footprint length. As mentioned earlier this influences the speed of dynamic planing and probably also that of viscous planing. The short length of the measuring tyre may also involve difficulties for the measuring tyre to utilize the potential hysteresis losses due to a coarse macrostructure.

The dry friction of both synthetic and natural rubber is temperature dependent. The difference is strongly non-linear, which illustrates of figure 2.8 in reference [4]. The synthetic rubber causes a higher brake number than natural rubber at temperatures above 0°C. Below the freezing point the relations are opposite. When a runway is covered with a loose contamination the friction is produced within the dry part of the footprint. Consequently a measurement with a syntetic rubber tyre may not be representative for a natural rubber tyre.

The difference in relative deflection influences primarily only the relative length and width of the footprint if the bending stiffness of the side walls can be neglected. However, difference in deflection may also change the draping of the tread around the macrostructure of the runway. This affects the ability of a tyre to utilize the potential friction, both the adhesion losses and the hysteresis losses.

The large difference in total wheel load is primarily of no significance if its influence on the draping characteristics may be disregarded. However, on thin ice and hoar frost covered runways with smooth microstructure and coarse macrostructure the total load may influence the wheels ability to peel off the contamination. This means uncontrolled conditions.

The difference in slip ratio is of small importance as long as the slip ratio is within 8-25%. At low brake numbers the ability of present anti-skid systems to take advantage of the potential friction is limited, because the systems permit the wheels to roll free for extended periods. When entering a slippery spot such a system produces a deep skid with a slip value far above the normal range. Figure 11 shows in principle the brake number vs. slip ratio in dry and in wet on a fine and a coarse textured runway.

The measuring vehicle normally operates at a relatively low constant speed. The touch-down speed of a modern heavy aircraft is large and it decelerates to a complete stop. When the available brake number is speed dependent it is consequently not possible to use the information from the vehicle without corrections. Presumably it is necessary to measure the brake number at more than one speed.

Due to the geometry of the footprint ($L/B \sim 1$) the drainage capability of the measuring tyre is better than that of the aircraft tyre. This will influence the possibility to forecast the planing speed of an aircraft from vehicle measurements by use of equation (15).

On an ice and snow covered runway heat in the aircraft tyre may produce a water film, which is not present below the measuring tyre. The reason is the large difference in deflection energy developed in the aircraft and the measuring tyre when rolling.

7.2. Force system on a wheel

Figure 12 shows the force system on a braked aircraft wheel or on the measuring wheel of a skiddometer vehicle.

The force by which a braked wheel affects an aircraft is

$$X = F \tag{21}$$

where $$F = F_R + F_F + F_S \tag{22}$$

or F_R = rolling resistance

F_F = hydrodynamic drag

F_S = slide friction

During a normal landing F_S is predominant. Mostly F_F is neglected. It is only necessary to consider F_F if the contamination layer is very deep.

A skiddometer wheel is forced to rotate with a lower angular speed than the free rolling speed. This causes a slide friction force in the tyre-ground contact surface and a torque in the wheel axle. The moment equilibrium about the centre of the wheel is

$$T = F \cdot r - N \cdot e \tag{23}$$

which together with (22) and (2) gives

$$T = r(F_F + F_S) \tag{24}$$

By neglecting F_F and by introducing the concept of brake number according to (3), equation (24) converts to

$$f_S = r \cdot \frac{T}{N} \tag{25}$$

From (25) it is obvious that no information about the rolling resistance is available, if the torque T is used as the measuring quantity. To get the rolling resistance included it is necessary to measure the drag force between the wheel and vehicle. Excluding F_F this may be expressed by

$$X = F_R + F_S \tag{26}$$

or in brake number by

$$(f_R + f_S) = \frac{X}{N} \tag{27}$$

In the skiddometer vehicles used in the present investigation, the torque is the measured information. By a calibration procedure it is expressed as a brake number (see (25)). The neglecting of f_R is justified by the fact that f_R normally is < 0.10.

8. BRAKE VEHICLE MEASUREMENTS

8.1. Measuring method and some conclusions

The vehicle measurements in the report are almost completely from equipment of skiddometer type. Exceptions are some measurements made with Tapley-meters. The skiddometer principle means that the measuring wheel is forced to rotate with a constant slip, 12-17% depending on model of vehicle. The driving torque is measured and evaluated into a brake number (see par. 7.2.). An integrator which

evaluates the mean value of the brake number is a part of the equipment. The runway is normally divided into three equal distances and the mean values of the brake number for each distance are recorded. Furthermore the local brake number along the runway is recorded on a strip-chart recorder. The Saab Friction Tester also records the momentary speed after each 100 meters. The measurements in this report have all been made at constant speed.

The result of a measurement with a measuring vehicle represents nothing but the brake number of the wheel at the occasion of the measurement. On loose contaminations it is not possible to apply the measured brake numbers without corrections when predicting the brake distances of aircraft. The most important parameters which influence the measurement are inflation pressure and speed.

Skiddometer measurements on different types of runways and at different speeds (30-120 km/h) have confirmed:

1. that water on a runway with smooth microstructure and fine macrostructure produces brake numbers < 0.40 down to low speed (30 km/h) and that rubber deposits, painted areas, dust and mud aggrevate the situation.

2. that ice on the same type of structures becomes very slippery if contaminated with water or slush.

3. that a runway contaminated with compacted snow or ice causes brake numbers > 0.40 at temperatures low enough to prevent forming of a water film when the wheel passes and that a layer of dry snow does not deteriorate the brake number.

4. that a wet runway with harsh microstructure and coarse macrostructure and with transverse slope (> 1.5%) causes brake numbers of > 0.40 within the speed range 30-120 km/h.

Details about the measurements behind the conclusions above may be found in ref. [1] and in the working papers behind that report.

In table 1 the inflation pressure of the measuring tyre is stated to be 120 kPa. Tyres (4.00-8") with this pressure, manufactured of synthetic rubber and provided with a diamond shaped tread pattern, have during several years been standard in Sweden on vehicles of type BV-11 or Friction Tester for runway brake number measurements. Since the fall of 1979 and as a consequence of measurements which will be presented later on in the text ribbed natural rubber tyres with an inflation pressure of 700 kPa now replace the former. The specification of the new tyre is presented in figure 13. The standard measuring speed in Sweden has also been increased from 65 to 95 km/h.

8.2. Comparative measurements between BV-11 and BV-6

To investigate the influence of inflation pressure and to some extent the influence of wheel loading a series of measurements

during winter conditions were performed with two types of vehicles BV-11 and BV-6. Both are skiddometer type trailers and the differences are tabulated in table 2.

During the testing the inflation pressure was changed from 120 kPa to 600 kPa (synth. tyres) at constant wheel loads in both vehicles.

The test results indicated:

1. that the vehicles at the same inflation pressure did not indicate any significant differences in measured brake numbers.

2. that an increase in inflation pressure up to 600 kPa did not influence the test results on a clean runway below the freesing point ($f > 0.90$), on compacted snow and coarse textured ice ($f \sim 0.35$) or on smooth ice with water ($0.04 < f < 0.19$).

8.3. Measurements with low and high pressure tyres

The tests in 8.2. concerned the influence of inflation pressure on dry and wet smooth runways. As mentioned no significant differences were obtained. To investigate if the conditions were different on runways with loose contaminations the investigation was continued with comparative measurements between tyres with an inflation pressure of 120 and 800 kPa respectively. The low pressure tyre was of synthetic rubber and the high pressure tyre of natural rubber. Vehicles of type BV-11 and Friction Tester were used.

Four types of runway conditions were tested and with the following results:

1. At a temperature of -1°C on a clean asphalt runway with harsh microstructure and coarse macrostructure and at the speeds 60 and 120 km/h the low pressure tyre gave $f = 1.06\text{-}1.08$ and the high pressure $f = 0.90\text{-}0.91$. Due to the different rubber mixtures and the differences in inflation pressure the result is expected. The difference in tread pattern may also slightly have influenced the figures. See table 26 in ref. [1].

2. On hard packed snow and ice, at a temperature of -1°C and at a speed of 60 km/h the low pressure tyre measured $f = 0.35$ and the high pressure $f = 0.38$. See table 27 in ref. [1]. One should not expect any significant difference in braking number on this type of dry contamination. The size of the brake numbers indicate that no water was present. At the current temperature natural and synthetic rubber produces approximately the same dry friction losses.

3. On compacted snow with a 5 mm layer of wet snow and at a temperature of -1 to 0°C the low pressure tyre measured a mean value of $f = 0.13$ and the high pressure tyre $f = 0.22$. It appears from table 28 in ref. [1] that the speed also was changed during these tests. The results indicate that the high pressure tyre got a better contact with the runway through the water film than the low pressure tyre.

4. On a layer of 10 mm slush on compacted snow and at a temperature of +1°C the low pressure tyre measured f = 0.01 and the high pressure tyre f = 0.22. The results (see table 29 in ref. [1]) indicate that the low pressure tyre was planing completely but the high pressure tyre only partially. The fact that the brake number did not decrease with increasing speed indicates that the macrostructure is coarse and that the high pressure tyre also could utilize some hysteresis losses.

The conclusion drawn from the tests are that on loose contaminants the inflation pressure of the tyre strongly influences the measured brake numbers.

8.4. The high pressure tyre Friction Tester Aero

The high pressure tyre has later been developed further. Its present characteristics are shown in figure 13. In comparison with the tyre used in 8.3. the two outermost ribs are removed causing a decrease in the bending stiffness of the side walls. Figure 10 illustrates the footprint of the 6-ribbed tyre in different states of dynamic planing. Comparison between figures 9 and 10 indicates that the planing conditions are heavily influenced by the inflation pressure. The 4-ribbed tyre is marketed under the trade name "Friction Tester Aero".

Some results from comparative tests with this tyre, which now is the standard measuring tyre for runway brake number testing in Sweden, the old low pressure tyre and aircraft are presented in paragraphs 9.4. and 9.5.

9. COMPARATIVE TESTS BETWEEN AIRCRAFT AND MEASURING VEHICLES

To study relations between decelerations of aircraft and simultaneously vehicle measured brake numbers during different meteorological conditions and on differently contaminated runways a number of comparative tests were made. Aircraft in ordinary line traffic with passengers were utilized on different airports in Sweden and Norway.

Three different methods were used to determine the deceleration of the aircraft.

1. A speedometer pick-up on the nose gear measured the momentary speed and calculated automatically the elapsed braking distance.

2. An accelerometer positioned in the passenger cabin measured the momentary deceleration of the aircraft.

3. The mean value of the deceleration was determined by the pilot from the braking distance used.

9.1. Comparative braking tests between Fokker F-28 and measuring vehicles of type BV-11

During the winter seasons of 1974/75 and 1975/76 comparative braking tests were performed by use of a Fokker F-28 aircraft and measuring vehicles of type BV-11 provided with low pressure tyres. The aircraft was equipped with a speedometer pick-up on the nose gear and an accelerometer in the passenger cabin. The electronic equipment also recorded the speed when the braking was initiated and the elapsed braking distance. Furthermore the momentary speed and deceleration vs. time were recorded on strip-chart recorders. The aircraft was braked at a speed of 100 knots (indicated speed on the speedometer of the aircraft) and the brakes were used with maximum braking until a complete stop. The recorded braking distance was later corrected for zero wind, sea level, +15°C and standard landing weight. From the deceleration records the mean values for the speed range 100-30 knots were calculated. Spoilers and flaps were in landing position. Before and after each test vehicle brake number measurements were performed.

The test results are recorded in tables 30 and 31 in ref. [1] and in figures 14 and 15 of the present report. The measured and corrected brake distances are made dimensionless by dividing by the certified brake distance. The curves are subjectively drawn to represent mean values. The decelerometer curve should terminate in a point (or points) on the vertical axis equivalent with the influence of rolling resistance and aerodynamic drag. A similar point valid for the brake distance, when $f = 0$, should be located to the right of the figure. The comments below supplement the test points in the figures.

Points 1, 2 and 3 in figures 14 and 15. Landings on a wet runway (Visby) with coarse macrostructure. The short landing distances show that no hydroplaning was present. The measuring vehicle also measured representative brake numbers. The temperature was +9°C.

Point 4. Landing on a wet runway (Bromma) with relatively fine macrostructure and at +8°C. No planing occurred.

Points 5 and 6. Landings on a wet concrete runway (Arlanda) with very smooth microstructure and very fine macrostructure. The aircraft was planing down to low speeds (~ 30 knots), and the brake numbers were low down to full stop. The brake numbers measured at 120 km/h predict the braking ability of the aircraft fairly well. The points 5' and 6' represent brake number measurements made at a speed of 60 km/h. The incongruity at 60 km/h may depend on the difference in tread patterns. The mean value of the brake number of the aircraft calculated from the brake distance is ~ 0.18 compared with the vehicle measured value of 0.64 (60 km/h). Even if the aircraft normally only can utilize half the brake number as a measure of deceleration it is difficult to explain the difference. The temperature was +7.6°C.

Point 7. Same conditions as in point 4. Bromma Airport.

Points 8 and 9. Landings on the same runway (Visby) as in point 1 and 2, but during dry conditions and at +6°C. That the points do not coincide may be a measure of the accuracy of the test method.

Point 10. Same runway (Bromma) as point 5 (7) and at a temperature of +6°C. The unexpected long braking distance of the aircraft may depend on water puddles due to the absence of transverse slope along the runway. Such puddles cause temporary hydroplaning and deep skids due to imperfection of present day anti-skid systems. The measured brake number indicates that the measuring vehicle was not planing to the same extent. Due to the temperature (+6°C) the friction losses in the vehicle tyre were larger than in the aircraft tyre, but the whole difference cannot be explained from this point of view.

Point 11. Same runway (Arlanda) as in points 5 and 6. Similar conditions and same result. Point 11' represents brake number measurements at 60 km/h. The temperature was +3°C.

Point 12. A clean runway (Halmstad) with moderately fine macrostructure and a certain microstructure. The braking distance was short and the measured brake numbers high as expected, due to no speed dependence. The temperature was +5°C.

Point 13. Same runway (Bromma) as in point 4 (7, 10) but contaminated with ice and slush in patches and at +3°C. The braking distance was somewhat longer than that expected from the brake number measurements. This may depend on the slippery spots, which deteriorate the efficiency of the anti-skid system.

Point 14. Landing on a dry runway (Sundsvall) with patches of ice and at -9°C. The short braking distance and the high brake number may be explained by the low temperature which prevents forming of a water film on the ice.

Point 15. Same runway (Bromma) as in point 10 (4, 7, 13), but partly dry and with a smaller amount of water puddles. The temperature was +2°C. The aircraft was able to utilize the potential friction losses better than the measuring vehicle. The reason is not obvious.

Point 16. Landing on a runway (Umeå) with a certain macrostructure and contaminated with ice patches. The high brake number and short braking distance were probably dependent on the cleanness of the runway and the low temperature (-5°C).

Point 17. Landing on a runway (Skellefteå) with ice patches and at -6°C. A relatively large part of the braking distance consisted of ice patches. The braking distance was shorter than expected from the vehicle measurements. Due to its higher mean speed the aircraft may have utilized the potential hysteresis losses better than the measuring vehicle.

Point 18. Same runway (Bromma) as in point 4 (7, 10, 13). The temperature -1°C indicates that ice with water may have been present. The long braking distance of the aircraft may be a result of planing within the higher speed range.

Point 19. Same runway (Umeå) as in point 16, contaminated with ice patches. The high brake numbers were probably a consequence of the low temperature (-11°C).

Point 20. Same runway (Skellefteå) as in point 17 (19) and at +1°C. Also here, with wet snow on ice and compacted snow, the braking distance was somewhat less than expected from the vehicle measurements.

Point 21. Same runway (Umeå) as in point 16 (19), but contaminated with dry snow on ice. The reported temperature +1° was probably higher than the runway temperature. Otherwise the brake number should have been lower due to a water film or wet snow.

Point 22. Same runway (Skellefteå) as in points 17 and 20. The conditions were practically identical and it is difficult to explain the differences. The temperature was -2°C.

Point 23. Same runway (Bromma) as in point 18 (4, 7, 10, 15), contaminated with ice patches and at +1°C. The braking distance of the aircraft was somewhat shorter than expected.

Point 24 and 25. Same runway (Umeå) as in point 21 (16, 19) and at -4°C. The runway was reported wet. The high measured brake numbers and short braking distances indicate an efficient runway structure.

Point 26. Same runway (Umeå) as in points 24 and 25, but clean and dry and at a temperature of 0°C. The friction losses are somewhat higher than in points 24 and 25. The small differences confirm the assumption of an efficient structure also when damp or wet.

Point 27. Same runway (Skellefteå) as in point 17 (20, 22) and at 0°C. The reason why, also on urea slush, the braking distance of the aircraft was shorter than expected from the vehicle measurements, was probably due to the capability of the aircraft to utilize the potential hysteresis losses.

Point 28. Same runway (Bromma) as in point 4 (7, 10, 13, 15, 18, 23) contaminated with ice patches and at +3°C. The measuring vehicle prediction agreed with the braking distance measured.

Point 29. Same runway (Umeå) as in point 16 (19, 21, 24, 25, 26) contaminated with dry snow on ice and at low temperature (-13°C). Despite the low temperature, the brake numbers were low. The dry snow may have behaved as a loose contamination. The vehicle measurements and the brake distance of the aircraft agreed well, indicating that the friction on dry snow is not speed dependent at low temperature.

Point 30. Same runway (Skellefteå) as in point 17 (20, 22, 27) contaminated with dry snow on ice at -13°C. The reason why the brake number was not higher may depend on the dry snow behaving as a loose contamination. The aircraft seems to have utilized the potential friction losses better than the vehicle. This may depend on hysteresis losses.

Point 31. Same runway (Skellefteå) as in point 30, contaminated with dry snow and at -25°C. That the friction losses were not larger may depend on the ability of the dry snow to behave as a loose contamination.

Point 32. Same runway (Bromma) as in point 4 (7, 10, 13, 15, 18, 23, 28) contaminated with dry snow at a temperature of -11°C. The brake number was low probably due to the dry snow and the low temperature. The difference between the measurements and the expected result may express the accuracy of the method of investigation.

Point 33. Same runway (Umeå) as in point 16 (19, 21, 24, 25, 26, 29) contaminated with ice and at a temperature of -8°C. The brake distance was shorter than expected. It is difficult to explain the difference.

Point 34. Same runway (Umeå) as in point 33 with practically the same contamination and at -7°C. The brake distance agreed fairly well with the expected.

Point 35. Same type of runway (Umeå) as in points 33 and 34 contaminated with dry snow on ice (-9°C). The measured brake distance was approximately the expected.

Point 36. Same runway (Umeå) as in point 35 contaminated with ice and at -9°C. The measured brake distance and measured brake number correlated well. On a clean runway the friction losses should have been higher.

Point 37. Same runway (Bromma) as in point 4 contaminated with ice patches and at -5°C. The short braking distance and the high brake number measured indicate that the total length of the ice patches must have been small.

The results presented in figures 14 and 15 indicate that brake numbers measured by use of measuring vehicles equipped with low pressure tyres on runways with dry contaminations correlate fairly well with brake distances of aircraft. On water covered ice, wet snow or water, where the potential friction losses are speed dependent, the measuring vehicles seem to make too high predictions. At low temperatures dry snow may behave as a loose contamination.

9.2. Comparative braking tests between Douglas DC-9-21 and measuring vehicles of type BV-11

Comparative braking tests were performed during the winter season 1975/76 by use of a Douglas DC-9-21 equipped with mark III brake system and measuring vehicles of type BV-11 with low pressure tyres. The aircraft was provided with a speedometer pick-up on the nose gear and an accelerometer in the passenger cabin. The speed, when the brakes were engaged, braking distance used and the time-histories of speed and deceleration were recorded. The braking started at 100 knots (indicated speed on the speedometer of the aircraft) and the aircraft was braked with maximum braking to a full stop.

The braking distances measured were later corrected to zero wind, sea level, +15°C and standard landing weight. From the deceleration records the mean values for the speed range 100-30 knots were calculated. Spoilers and flaps were in landing position and no reverse was used.

The test results can be found in table 32 in ref. [1] and in figures 16 and 17 of the present report. The brake distances are divided by the certified brake distance. The comments below supplement the test points in the figures.

Point 1. Runway (Tromsö) covered with ice, contaminated with snow and at -5°C. The measuring vehicle and the aircraft correlated well. The brake numbers were very low, probably due to forming of water films in the footprints.

Point 2. Winter runway*) (Alta) contaminated with dry snow, at low temperature (-14°C). The measurements correlated well.

Point 3. Winter runway (Kirkenes) contaminated with dry snow, at low temperature (-18°C). The measurements correlated well. The brake number was fairly low.

Point 4. Runway (Tromsö) covered with ice, contaminated with snow. The temperature changed during the test from -4 to 0°C. The measuring vehicle recorded a higher brake number (0.21) than the aircraft (deceleration number 0.08 calculated from the brake distance used). Forming of water in the footprint was probably the cause of the discrepance.

Point 5. Runway (Tromsö) contaminated with ice patches and snow. The temperature was -7°C. The brake numbers were fairly low and the correlation good.

Point 6. Winter runway (Kirkenes) contaminated with dry snow and loose sand. The temperature was -23°C. The correlation was good but the brake number should have been higher. The reason might have been the loose sand.

Point 7. Winter runway (Evenes) contaminated with snow and at -2°C. Measured brake distance and measured brake number correlated fairly well. The brake numbers were higher than expected.

Point 8. Runway (Fornebu) contaminated with ice patches and at -4°C. The correlation was good and the brake numbers fairly high probably due to the characteristics of the microstructure and few ice patches.

Point 9. Runway (Tromsö) contaminated with 30 mm snow and at +1°C. The aircraft utilized a higher brake number than that predicted by the vehicle. Might eventually depend on a high rolling resistance due to the thick contamination.

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*) The words "winter runway" are used to designate a runway with a surface consisting of a solid mixture of ice and sand.

Point 10. Winter runway (Alta) contaminated with compacted snow and at -13°C. The correlation was good.

Point 11. Winter runway (Kirkenes) contaminated with snow and at -20°C. The correlation was good and the brake numbers fairly high.

Point 12. Winter runway (Alta) contaminated with snow and at -13°C. The correlation was relatively good.

Point 13. Runway (Fornebu) contaminated with ice patches during snowfall and at 0°C. The correlation was good and the brake numbers fairly high.

Point 14. Runway (Tromsö) contaminated with compacted snow and at -16°C. The aircraft utilized the potential friction losses better than the vehicle. The correlation was fairly good.

Point 15. Winter runway (Kirkenes) contaminated with wet snow and at -5°C. The braking distance was longer than predicted. The braking number of the aircraft might have been speed dependent due to the wet snow.

Point 16. Winter runway (Alta) contaminated with snow and at -16°C. The correlation was fairly good.

Point 17. Runway (Tromsö) contaminated with compacted snow and ice patches and at -14°C. The correlation was good and the brake number fairly low.

Point 18. Runway (Tromsö) with the same conditions as in point 17. The aircraft used in 17 a shorter and in 18 a longer braking distance than predicted by the vehicle. The difference may be an expression of the accuracy of the investigation method.

Point 19. Winter runway (Kirkenes) contaminated with compacted snow and at -22°C. The braking distance was somewhat longer than predicted.

Point 20. Runway (Tromsö) contaminated with compacted snow and at -9°C. The aircraft needed a longer brake distance than predicted.

Point 21. Runway (Tromsö) contaminated with ice and sanded. The temperature was +2°C. The correlation was poor and the brake number unexpectedly high.

Point 22 and 23. Winter runway (Alta) at +1°C. The correlations were good.

Point 24. Runway (Tromsö) contaminated with ice and at +1°C. The brake number was unexpectedly high and the correlation poor.

Point 25. Winter runway (Evenes) contaminated with wet snow and at +3°C. The brake number was fairly large and the correlation good.

Point 26. Runway (Fornebu) contaminated with ice patches and at -3°C. The brake number was unexpectedly high and the correlation relatively good.

Point 27. Runway (Tromsö) contaminated with ice and water. Temperature 0°C. The correlation was relatively good and the brake number low as expected.

Point 28. Winter runway (Alta) contaminated with wet snow and at -4°C. The aircraft could not be braked maximally due to yaw-stability disturbances caused by strong air turbulence.

Point 29. Winter runway (Kirkenes) contaminated with compacted snow and at -4°C. The correlation was good and the brake number relatively large.

Point 30. Winter runway (Alta) contaminated with ice patches and at -4°C. The correlation was relatively good.

Point 31. Runway (Tromsö) contaminated with ice and at +3°C. The correlation was fairly good and the brake number relatively high.

Point 32. Winter runway (Evenes) contaminated with wet snow and at +3°C. The correlation was good and the brake number lower than expected.

Point 33. Runway (Fornebu) contaminated with ice patches and at +2°C. The correlation was poor and the brake number very high. The ice patches must have been few and of limited extension.

Point 34. Runway (Tromsö) contaminated with ice patches and at +1°C. The correlation was good.

Point 35. Winter runway (Kirkenes) contaminated with compacted snow and at -5°C. The correlation was good and the brake number relatively low.

Point 36. Runway (Tromsö) contaminated with ice patches and at +1°C. The correlation was good. The conditions were the same as in point 34.

Point 37. Winter runway (Evenes) at +1°C. The correlation was good and the brake number high.

Point 38. Runway (Fornebu) contaminated with ice patches and at -1°C. The correlation was fairly good and the brake number very high.

Point 39. Winter runway (Kirkenes) contaminated with snow and at 0°C. The correlation was good and the brake number relatively high.

Point 40. Runway (Lakselv) partly clean partly contaminated with snow at -5°C. The correlation was good and the brake number very high. This runway is grooved and has an efficient structure.

Point 41. Winter runway (Kirkenes) contaminated with dry snow and at -5°C. The correlation was relatively good and the brake number high. Yaw stability disturbances may have occured due to strong winds.

Point 42. Runway (Lakselv) clean and at -5°C. The correlation was relatively good and the brake number high. Yaw stability disturbances may have occurred due to strong winds.

Point 43. Winter runway (Kirkenes) with ice patches and at -2°C. The correlation was poor and the brake number high. Yaw stability disturbances may have occurred due to strong winds.

The correlation between measured aircraft brake distances and vehicle measured brake numbers is good on winter runways which are more or less dry. Exceptions are tests where yaw stability disturbances have occurred due to air turbulence. Measured brake distances seem to be longer (< 25%) than predicted by the measuring vehicles if the runways are contaminated with compacted snow. Water on ice causes very long brake distances.

9.3. Comparative braking tests between Boeing 737-200A and measuring vehicles of type BV-11

Comparative braking tests were performed during the winter season 1975/76 by use of a Boeing 737-200A equipped with mark III brake system and measuring vehicles of type BV-11 with low pressure tyres. Occasionally the brake numbers were measured with Tapley-meters, when no BV-11 was available. The aircraft had a speedometer pick-up on the nose gear. The speed when the brakes were engaged, braking distance and the time history of the momentary speed were recorded. The braking started at 100 knots (indicated speed of the speedometer of the aircraft) and the aircraft was braked with maximum braking to a full stop. The brake distance measured was later corrected to zero wind, sea level, +15°C and standard landing weight. Spoilers and flaps were in landing position and no reverse was used.

The tests are recorded in table 36 in ref. [1]. Figure 18, in the present report, shows the measured vehicle brake numbers vs. measured and corrected brake distances divided by certified brake distance. Figure 19 is the longitudinal decelerations calculated from the brake distances used. The comments below supplement the test points in the figures.

Point 1. Runway (Stavanger), clean and dry and at +3°C. The microtexture is smooth and the macrotexture fine. The correlation between aircraft and measuring vehicle was good.

Point 2. Runway (Bodö) contaminated with wet snow and slush and at +2°C. The correlation was good. The high brake number indicates a frozen mixture of ice and sand and a limited amount of slush. No planing seems to have occurred.

Point 3. Runway (Tromsö) wet and at +4°C. The Tapley-meter value correlated well with the measured brake distance. The brake number was high and no planing seems to have occurred.

Point 4. Same runway (Tromsö) as in point 3, but at a temperature of +1°C and contaminated with slush on ice. The Tapley-meter value measured was far too low. Due to the low tyre pressure the car was probably viscous planing but the aircraft not. A BV-11 with a low pressure tyre should have given the same result. The brake distance of the aircraft was very short, possibly due to a frozen mixture of ice and sand below the slush.

Point 5. Same runway (Tromsö) as in point 3, but at 0°C and contaminated with patches of wet snow. Also here the Tapley-meter gave a too low value. The car was probably planing.

Point 6. Runway (Bodö) contaminated with patches of wet snow and slush. The vehicle measured a lower brake number than the aircraft experienced.

Point 7. Winter runway (Evenes) contaminated with snow and at -4°C. The runway surface consisted of a frozen mixture of ice and sand and the brake number was relatively high. The correlation was fairly good.

Point 8. Winter runway (Badufoss) contaminated with patches of wet snow and at -4°C. The correlation was good and the brake number relatively low.

Point 9. Runway (Bodö) contaminated with ice and snow and at -4°C. The correlation was good and the brake number relatively low.

Point 10. Same winter runway (Badufoss) as in point 8, but contaminated with dry snow and at +3°C. The correlation was good. The long braking distance and low brake number indicate water on the runway.

Point 11. Runway (Ålesund) contaminated with snow and slush and at 0°C. The good correlation and the high brake number indicate that no planing was present.

Point 12. Runway (Kristiansund) in wet and at +1°C. The correlation was relatively poor and the measured brake number high. Some planing of the aircraft may have occurred. The runway is grooved.

Point 13. Runway (Tromsö) contaminated with 10 mm snow and at -3°C. The correlation was good and the brake number relatively low. A water layer may have been present, or have been formed by the wheel.

Point 14. Winter runway (Röros) contaminated with patches of wet snow and at +4°C. The correlation was good.

The correlation between measured airplane brake distances and measured brake numbers is good on dry winter runways.

Earlier experience from smooth, water contaminated runways indicated that measuring vehicles gave too high brake numbers probably depending on too low measuring speed. Some results in this chapter suggest the opposite experience on slush contaminated runways. This may

depend on the low inflation pressure in the measuring tyre causing viscous slush-planing down to low speed on runways with semiharsh microstructure.

9.4. Comparative braking tests between Airbus A-300B, Douglas DC-9-41 and vehicles with low and high pressure tyres

Comparative braking tests were performed during the winter season 1978/79 between an Airbus A-300B, a Douglas DC-9-41 and a measuring vehicle of type Friction Tester provided with high-pressure tyre (p = 700 kPa) on Luleå Airport. A few more tests were done with DC-9-41 on other airports. In these cases the brake numbers were measured with BV-11 vehicles equipped with low-pressure tyres (p = 120 kPa). Comparative tests between Apeco BV-11 and Saab Friction Tester both with low-pressure tyres have earlier been reported in ref. [13]. From that it appears, that the vehicles give equal results, when the conditions are equal.

The aircraft were equipped with an accelerometer in the passenger cabin. The momentary deceleration was recorded on a strip-chart-recorder and the mean deceleration was later calculated. The tests were performed with maximum braking from 50 knots to full stop. As a preparation for further testing with aircraft in line-traffic and without acceleration instrumentation the pilots were asked to determine the brake number subjectively from the brake distance used. The brake distances were determined from different types of runway distance markers. When the pilots made their determinations they were not aware of the results from the deceleration measurements or the vehicle brake number measurements.

Figure 20 shows the results from the tests on Luleå Airport. The comments below describe the test conditions. The numbers refer to table 37 in ref. [1]. The Luleå Airport's runways are constructed of asphalt with a semiharsh microstructure and a semicoarse macrostructure.

Point 3. Runway contaminated with ice patches and dry snow and at -18°C.

Point 4. Runway contaminated with a continuous layer of ice and dry snow and at -18°C.

Point 10. Runway contaminated with ice patches and at -24°C.

Point 1. Runway contaminated with ice and at -11°C.

Point 6. Runway contaminated with ice and with patches of dry snow and at -12°C.

Point 9. Clean runway with ice patches and at -23°C.

Point 20. Runway with ice patches and at -8°C. Light snowfall.

Point 22. Runway contaminated with ice patches and at -6°C.

All test points refer to dry runways and at low ambient temperature. The correlations between the measured decelerations of the aircraft and the brake numbers measured are good. The different levels of the correlation curves may depend on the different efficiencies of the brake systems and on the differences in landing gear configurations.

Figure 21 shows the same tests with DC-9-41 as in figure 20 and some additional tests, which were done on other airports during the same time period. In some cases the brake numbers were measured by use of BV-11 vehicles with low pressure tyres. The comments below illustrate the test conditions for the additional tests. The numbers refer to table 37 in ref. [1].

Point 5. Runway (Kiruna) contaminated with ice and snow patches and at -18°C.

Point 7. Clean runway (Arlanda) with patches of dry ice and at -9°C. This runway has got a new efficient texture by a scoring process.

Point 8. Runway (Malmö) contaminated with snow and at -4°C. The correlation was poor and the brake number low. Vehicle BV-11 was used.

Point 11. Runway (Fornebu) contaminated with ice patches and at -16°C.

Point 12. Winter runway (Evenes) contaminated with 5 mm snow and at -12°C.

Point 13. Runway (Tromsö) contaminated with sanded ice and snow and at -12°C. The correlation was good and the brake number low.

Point 14. Runway (Trondheim) contaminated with ice and sanded, urea treated snow at 0°C. Vehicle BV-11 was used.

Point 15. Runway (Bodö) contaminated with sanded wet ice and at +3°C. The correlation was poor. Vehicle BV-11 was used.

Point 15. Runway (Bodö) contaminated with sanded wet ice and at +3°C. The correlation was poor. Vehicle BV-11 was used.

Point 16. Winter runway (Evenes) consisting of sanded wet ice at +2°C. The correlation was good.

Point 18. Winter runway (Evenes) consisting of sanded ice contaminated with a layer of slush and at +2°C. The brake number was low and the correlation good.

Point 21. Clean and dry runway (Kristiansand) at -18°C. The correlation was good. Vehicle BV-11 was used.

Point 23. Winter runway (Evenes) contaminated with sanded snow and at -5°C. The correlation was good, BV-11 showed 0.38 and Friction Tester 0.41.

Point 24. Winter runway (Evenes) contaminated with snow at -1°C. The correlation was good with the Friction Tester (0.37) and somewhat poorer with the BV-11 (0.28).

All tests in figure 21 refer to winter conditions and the contaminations were only in a few cases of such types that speed dependences should be expected. However, the results indicate that measurements by use of a high pressure tyre correlate better with the deceleration of braking aircraft than measurements with a low pressure tyre do, when the brake number is < 0.5 due to slippery contaminations.

Figure 22 shows a comparison between mean values of measured deceleration from 50 knots to full stop vs. pilot determined brake numbers. The curves are the same as in figure 20. The correlations are amazingly good and indicate that experienced pilots seem to be able to determine brake numbers from landing distances used, with a reliability good enough for the type of analysis made in this report.

Figure 23 shows a comparison between brake numbers determined by pilots and simultaneously vehicle measured brake numbers. The correlation between the pilots' determinations and the measurements made with high pressure tyres is good at least in the reported cases. The low pressure tyres cause much larger scatter.

9.5. Comparative braking tests between Douglas DC-9-41 and vehicles with low and high pressure tyres

A series of braking tests were carried out during the winter season 1978/79 by LFD (the Board of Civil Aviation in Norway) at Evenes Airport located in northern Norway. Pilots of landing aircraft of type DC-9-41 determined the brake numbers from the distances used when braking from 50 knots to full stop. The brake numbers were also measured by vehicles equipped with low and high pressure tyres. The test points presented in figures 24 and 25 are from table 38 in ref. [1]. It is not possible to draw from the table any directly significant conclusions of the influence of the tyre inflation pressure or the speed on the brake numbers. The reasons may be the surface structure with a mixture of frozen sand and ice and the absence of ample quantities of contaminating snow, slush or water. During the test period the temperature varied within -12 to +2°C. However, the figures illustrate that the results obtained with the low pressure tyre vs. pilot determined brake numbers scatter more than the results from the high pressure tyre.

10. CONCLUSIONS

The following conclusions may be drawn from the investigations presented.

A) On a clean and dry runway the brake number is essentially determined by the adhesion losses in the tyre-ground contact

surface. A smaller part of the brake number is due to the hysteresis losses. A coarse (open) texture is a necessary condition for causing hysteresis losses. Dry snow and ice covered runways at low temperature may produce relatively high adhesion losses in aircraft tyres.

B) On a wet runway adhesion losses can only arise in that part of the footprint, where the water is completely displaced and dry contact established. The hysteresis losses are not primarily influenced by the presence of water. If the structure of the runway is smooth and closed, viscous planing may occur down to low speeds. This means low available brake numbers. The problem is exceedingly present on runways contaminated with thin slush layers, wet compacted snow or a wet layer of dust and mud.

C) The available brake number will be very speed dependent due to dynamic planing if the runway is contaminated with larger quantities of water or slush. The planing will be partial or total depending on the runway structure and the depth of the contaminating layer. Below a certain depth total planing does not occur up to current touch-down speeds.

D) Dry snow (crushed ice) at low temperature and loose sand deteriorate the available brake numbers particularly on smooth and close textured runways.

E) Clean and dry runways always give sufficient friction. The influence from loose contaminations such as water or slush is limited by a harsh microstructure and a coarse macrostructure. Harsh microstructure prevents viscous hydroplaning, but not always slush-planing or viscous planing due to compacted wet snow masking the microstructure. Coarse (open) macrostructure may prevent dynamic planing, at least for current precipitation intensities in northern Europe.

F) A runway should have harsh microstructure and coarse macrostructure. The transversal slope should be large. These characteristics improve the drainage quality of the runway, cause a high potential brake number and prevent viscous and dynamic planing. It is essential to avoid painting, which masks the microstructure, as much as possible. Rubber deposits have the same influence.

G) Measurements of brake numbers on clean and dry surfaces are not essentially influenced by the differences in parameter values of aircraft and measuring vehicles. This is also true for runways covered with ice or compacted snow if the temperature is low enough to prevent forming of water films.

H) When measuring brake numbers on loose contaminations such as wet snow, slush or water it is necessary to eliminate the influence from as many parameter differences as possible. Today this cannot be made by use of corrections. It is necessary to choose approximately the same parameter values in the measuring vehicle as are valid for current aircraft.

It is necessary to measure brake numbers at speeds as close as possible to the current speed range of aircraft. If the brake number is speed dependent it is necessary to measure at two speeds or more. The highest speed should be high enough to permit a judgement of planing tendences.

The inflation pressure is of great importance and it is relatively simple to use approximately the same pressure in the measuring vehicle as is used in aircraft. On loose contaminations, which are below "critical" depth, also the length of the footprint and the drainage path influences the result. It is also necessary to consider the influence of tread pattern on smooth and fine textured runways.

It is relatively easy to force the measuring wheel to roll with a slip ratio within the slip ratio range of antiskid systems of modern aircraft.

The adhesion losses of different rubber mixtures are different and are also temperature dependent. It is advisable to use the same type of rubber mixture in the measuring tyre as is used in aircraft tyres.

The dynamic planing process is influenced by the geometry of the deflected footprint. It is necessary to have approximately the same relative bending side-wall stiffness in the measuring tyre as in the aircraft tyres.

I) The results presented in the report show that brake numbers measured by use of a tyre, in which the characteristics mentioned below approximately meet that of an aircraft tyre, correlate better with the braking ability of an aircraft than tyres do, where those characteristics are different. This is true, at least on the types of contaminations, which were available for the tests presented.

Inflation pressure
Slip ratio
Tread pattern
Rubber mixture
Relative side-wall bending stiffness

J) Differences in brake numbers caused by differences in total load or tyre temperature cannot be predicted today.

K) Vehicle measurements must be up-to-date with the landings of the aircraft if the meteorological conditions change.

L) The knowledge about the influence of the different parameters of a tyre-runway combination on the brake number is still insufficient for reduction of unambiguous corrections between measuring tyres of present type and aircraft tyres. A feasible way, which has been applied to the new measuring tyre, is to choose approximately the same values of the different parameters in both the measuring tyre and the aircraft tyre. This permits large errors in the corrections.

M) Today no satisfactory transducers and reporting processes exist for reporting loose contaminations with a depth smaller than "critical". It is not possible to apply planing corrections without this information. It is also necessary to improve the reporting of the qualities of contaminations.

N) Theories available today are not fully taken account of. It is probably possible to get a better understanding of planing problems on contaminations with a depth smaller than the critical.

O) If reporting of brake numbers to pilots is of importance, it is necessary to continue the development of both measuring vehicles and applying processes.

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Table 1

Characteristic differences between the trailer BV-11 and aircraft used in the investigation.

	Vehicle BV-11	Aircrafts
Inflation pressure	120 kPa	700-100 kPa
Footprint	Rectangular 100 cm^2	Elliptical ~ 750 cm^2
" , length	5 cm	22 cm
Wheel diameter	0.41 m	0.8-1.2 m
Rubber type	Synthetic	Natural
Vertical deflection	Small ~ 12%	Large ~ 30-35%
Wheel load	1000 N	100 000 N
Slip ratio	Constant 17%	Variable 5-30%
Speed	~ 35 kt	120-0 kt
Tread pattern	Diamond shaped	Rilled
Deflection energy	Small	Large

Table 2

Differences between vehicles BV-11 and BV-6.

	BV-11	BV-6
Tyre dimension	4.00-8	7.50-14
Wheel load	1000 N	4930 N
Slip ratio	17%	12%

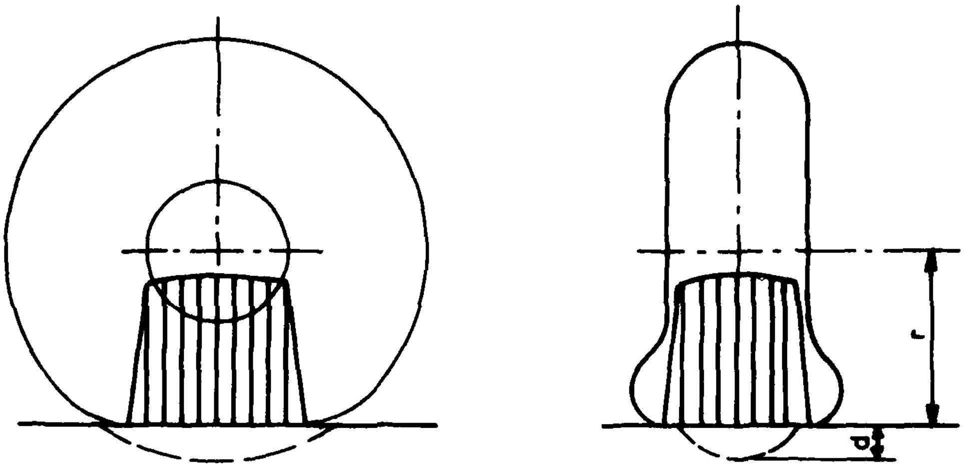


Fig. 1 The distribution of local pressure in the footprint area and the deflection of an aircraft tyre.

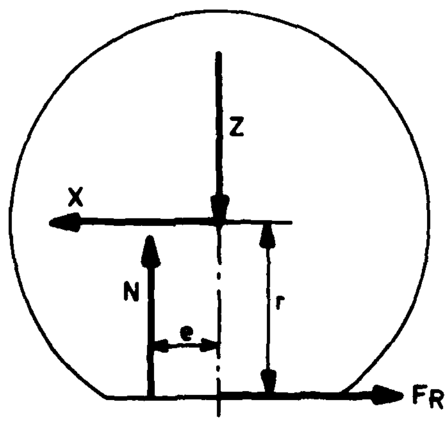


Fig. 2 Forces on a freely rolling towed wheel.

$$\begin{cases} Z = N \\ X = F_R \\ N \cdot e = F_R \cdot r \end{cases}$$

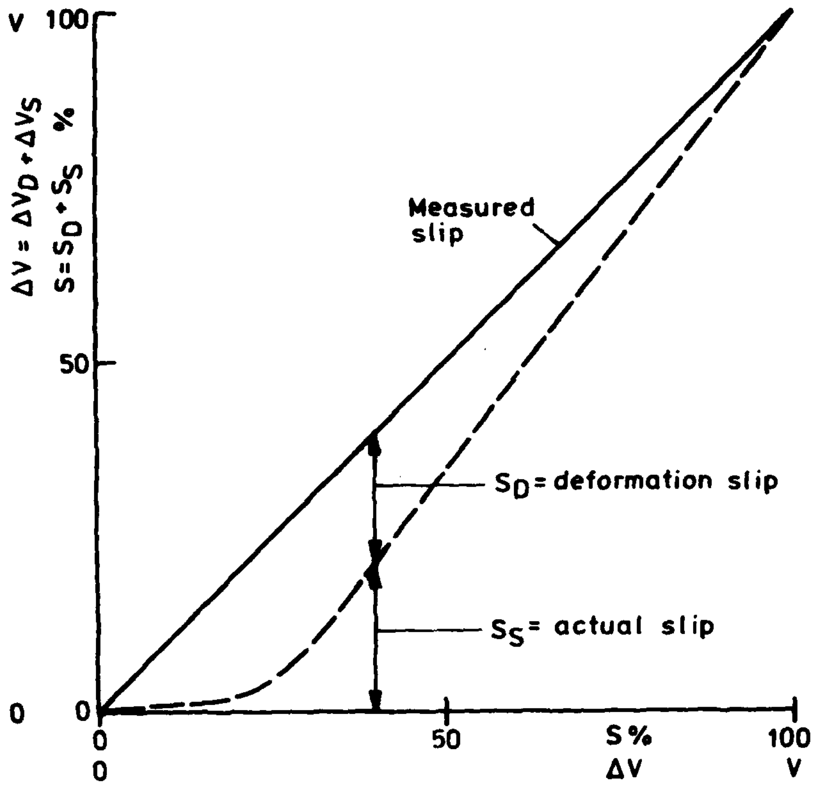


Fig. 3 Equivalent in principle with Fig. 7 in [5].

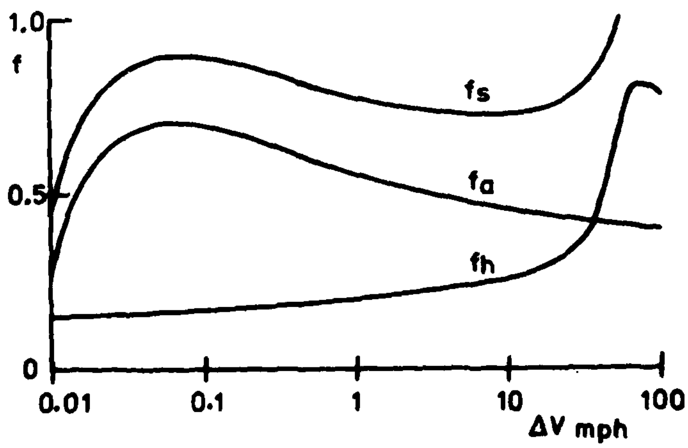


Fig. 4 Adhesion, hysteresis and total frictional numbers when a rubber block slides along a dry hard surface. From [5].

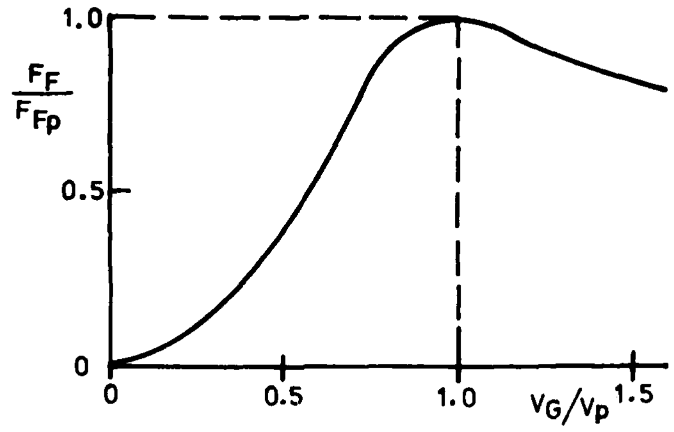


Fig. 5 Wheel fluid drag vs. speed.

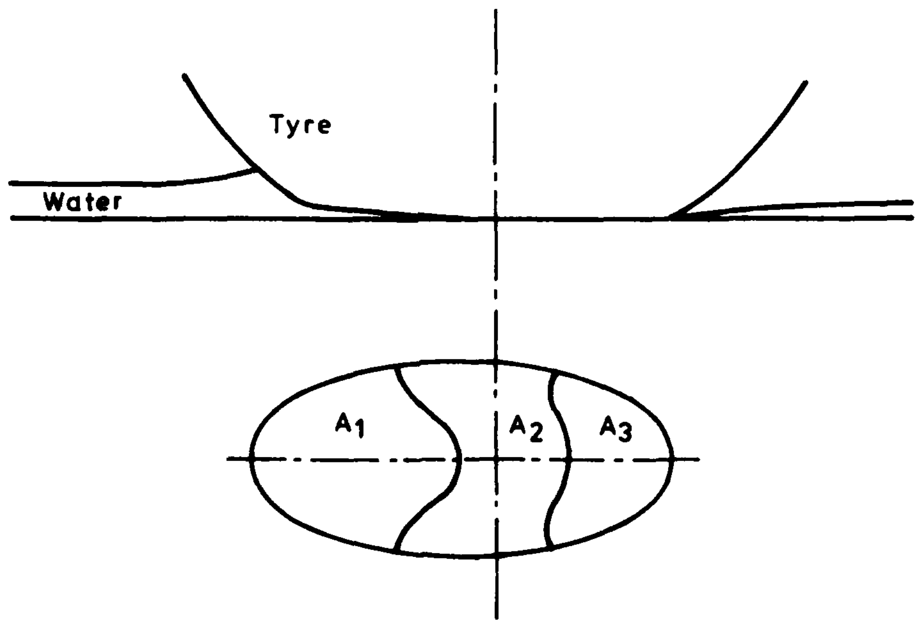
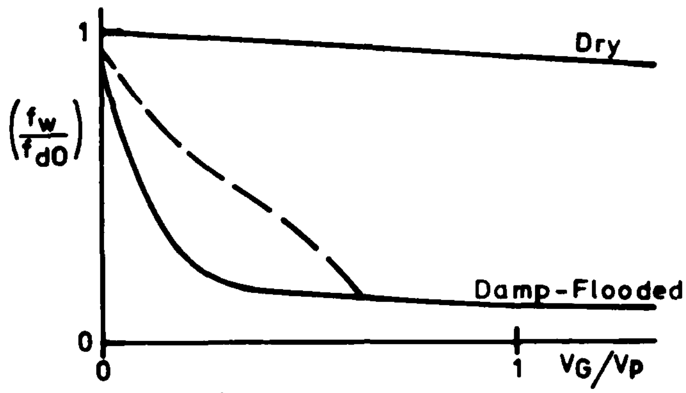
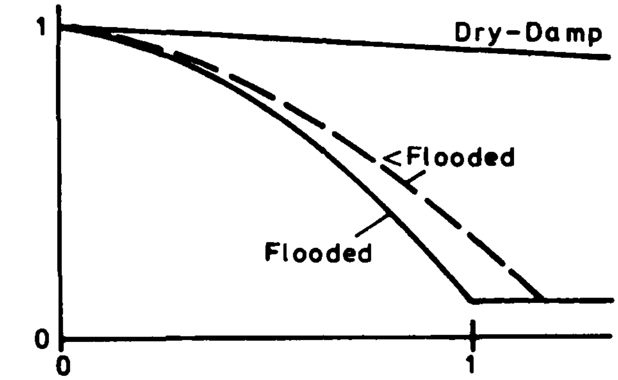


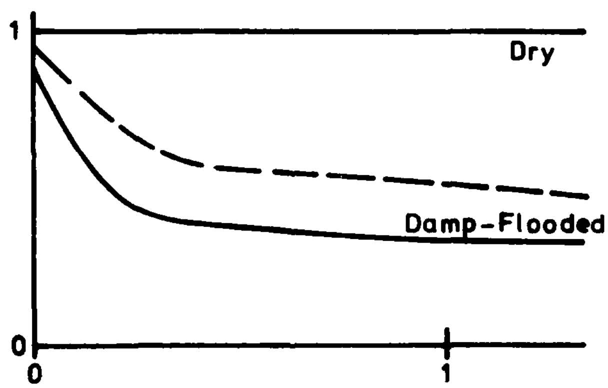
Fig. 6 NASA 3-zone model from [11].



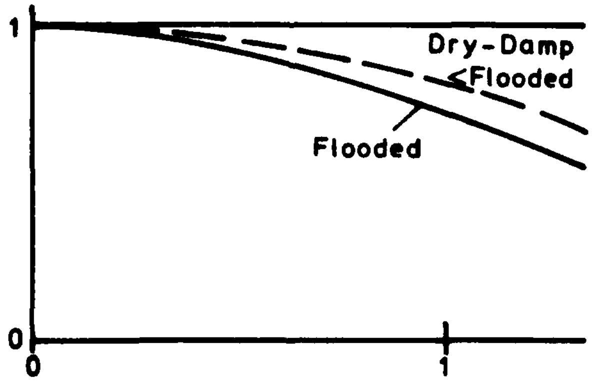
a) Smooth microtexture and closed macrotexture



b) Harsh microtexture and closed macrotexture



c) Smooth microtexture and open macrotexture



d) Harsh microtexture and open macrotexture

Fig. 7 Brake number vs. speed on differently textured runways.

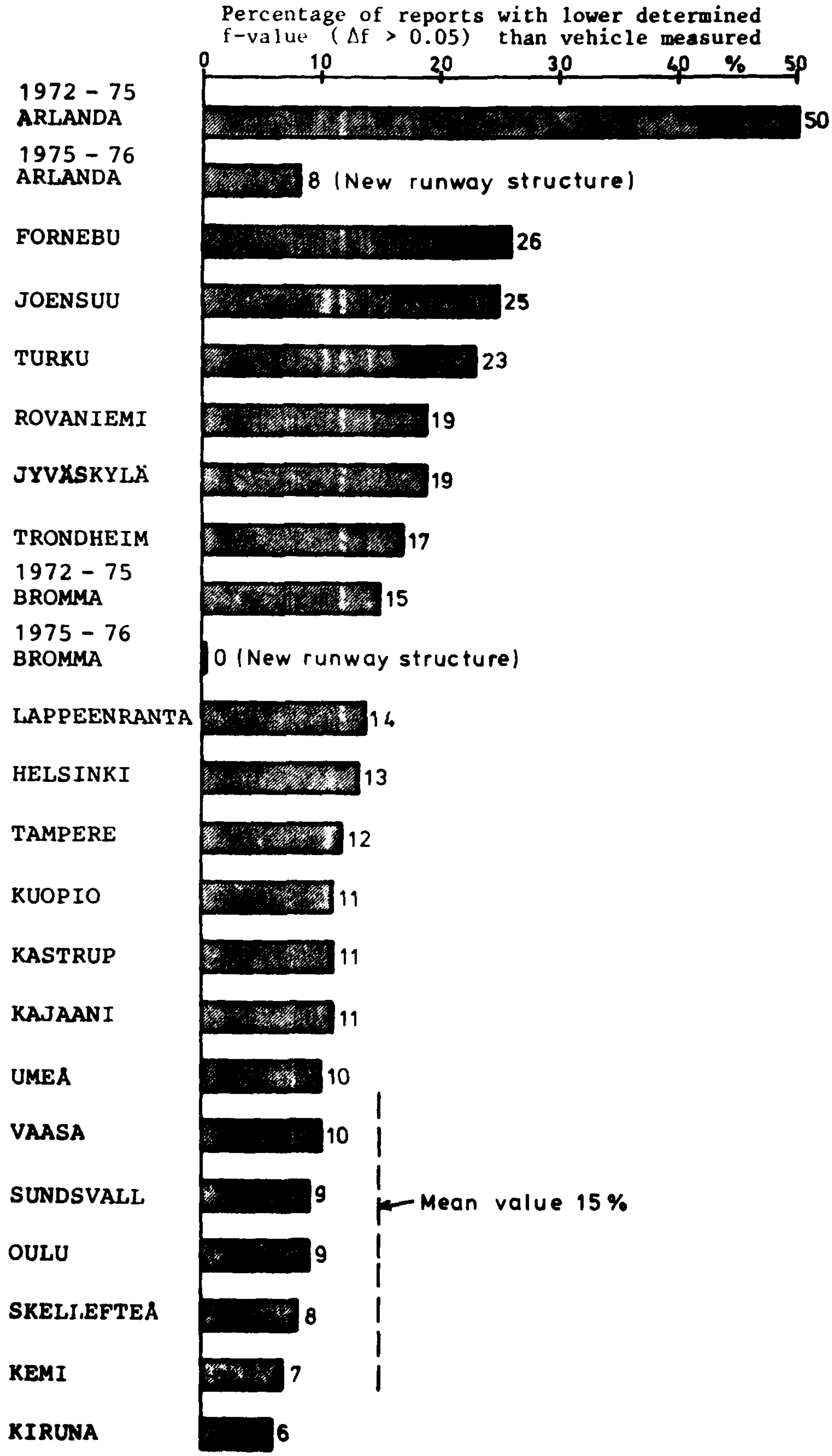


Fig. 8 Results from the pilots' report investigation 1972-76. Total number of reports 8696, number of complaints 1276 (15 %).

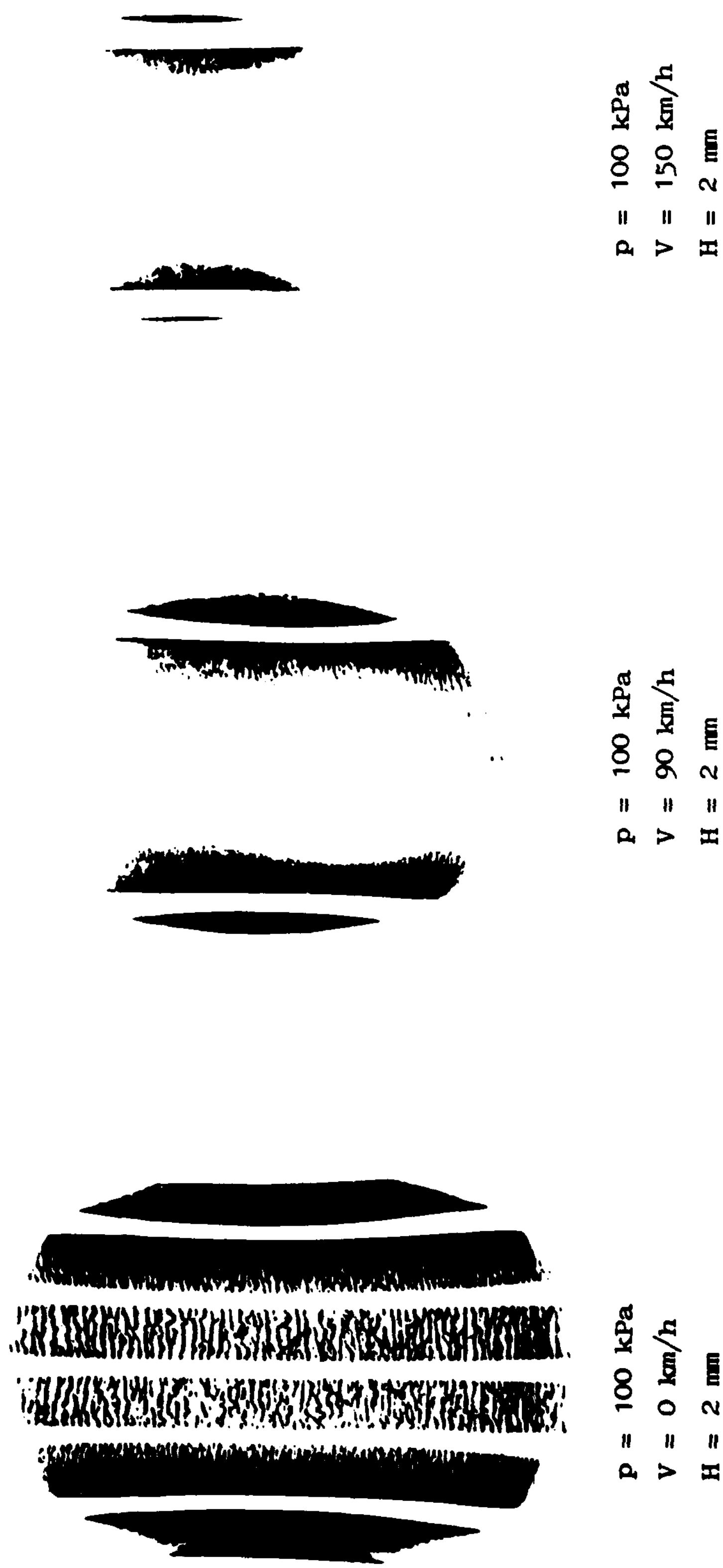


Fig. 9 Hydroplaning tests on a smooth glassplate. Early version of test tyre Aero with 6 ribs.

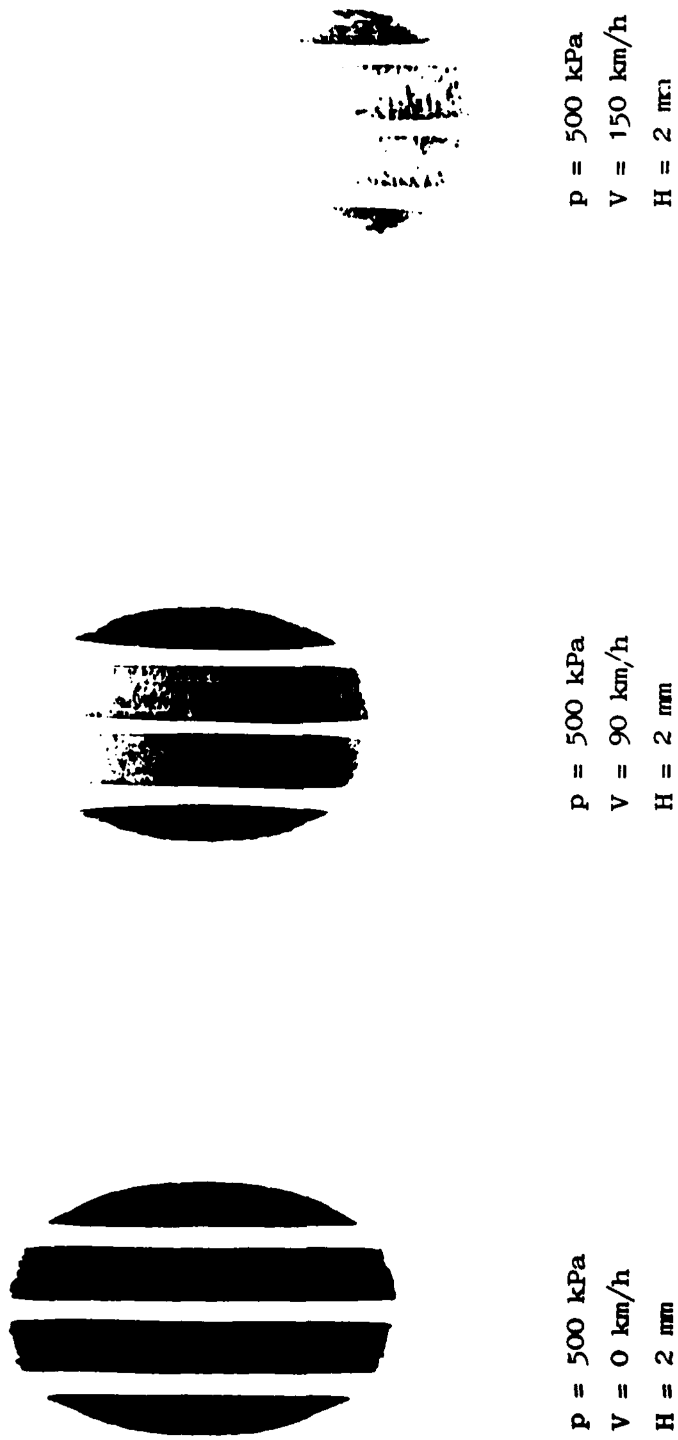


Fig 10 Hydroplaning tests on a smooth glassplate.
Early version of test tyre Aero with 6 ribs.

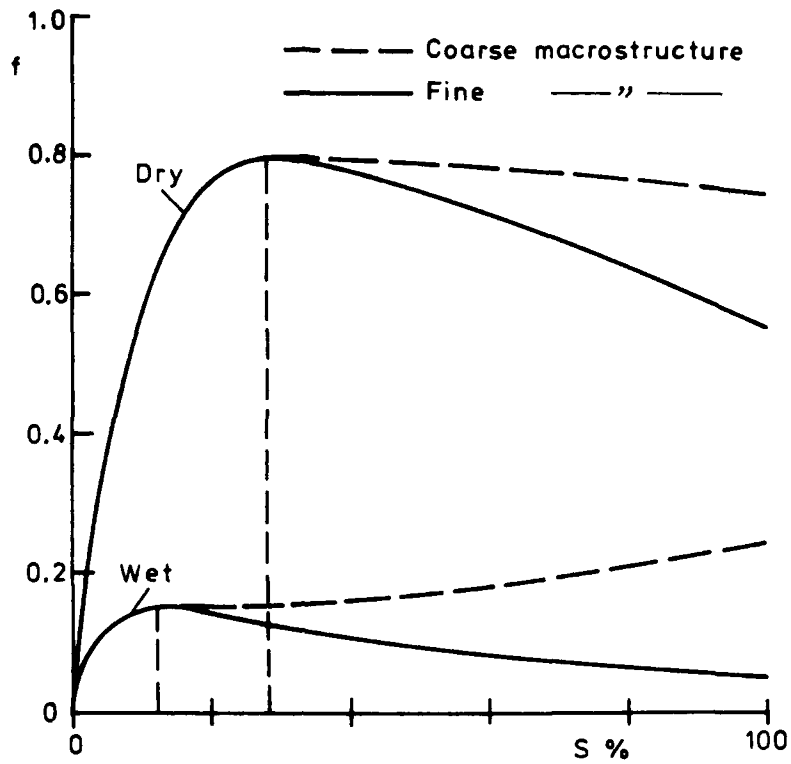


Fig. 11 Brake number vs. slip ratio in principle.

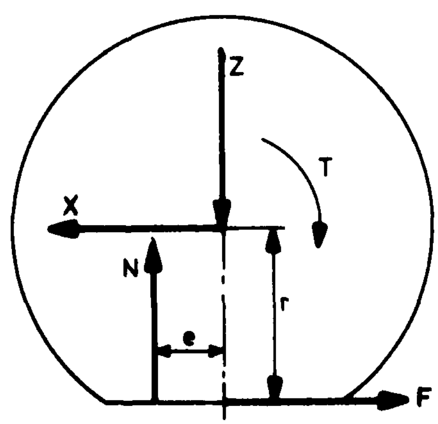


Fig. 12 Forces on a braked aircraft wheel or a skiddometer wheel.

$$\begin{cases} Z = N \\ X = F \\ N \cdot e + T = F \cdot r \end{cases}$$

1 Dimensions

1.1 Dimension 4.00–8"

1.2 Tire tread, see fig.

1.3 The tire is of diagonal type.

2 Physical requirements

2.1 Nominal load	1400 N
2.2 Working speed max.	120 km/h
2.3 Max speed (short time)	165 km/h
2.4 Max working pressure	7 bar
2.5 Ambiant temp.	−40°C - +40°C

3 Material

3.1 Natural rubber	
3.2 Hardness	60±2 shore

4 Markings

4.1 AERO

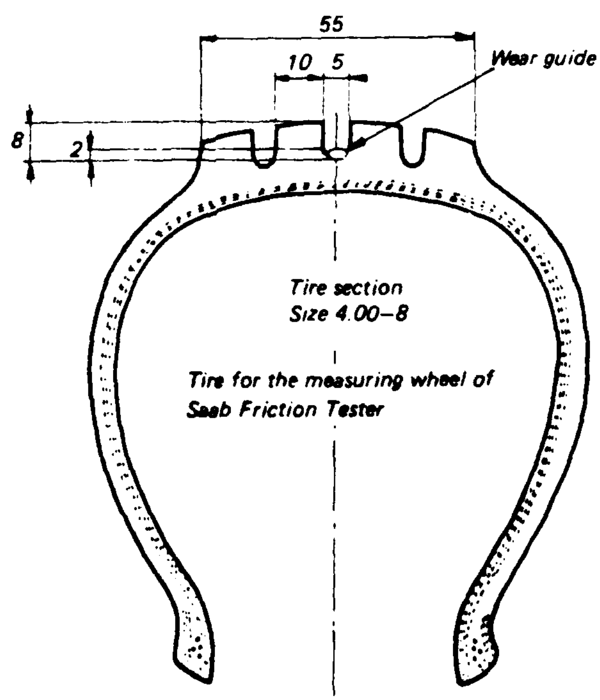


Fig. 13 Specification of measuring tyre Friction Tester Aero.

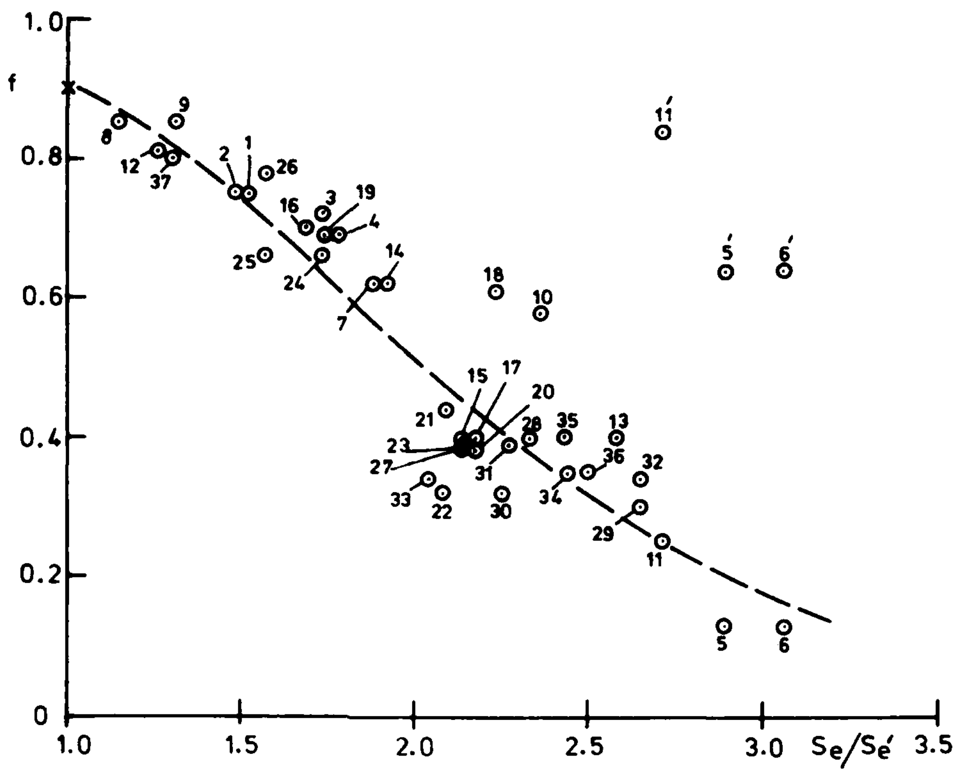


Fig. 14 Brake numbers measured with BV-11 (low pressure tyre) vs. relative brake distance of aircraft Fokker F-28.

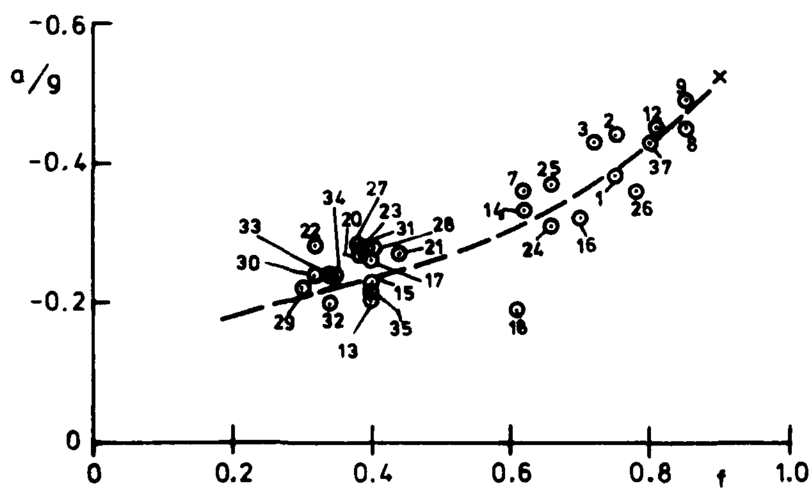


Fig. 15 Aircraft F-28 deceleration vs. BV-11 measured brake numbers.

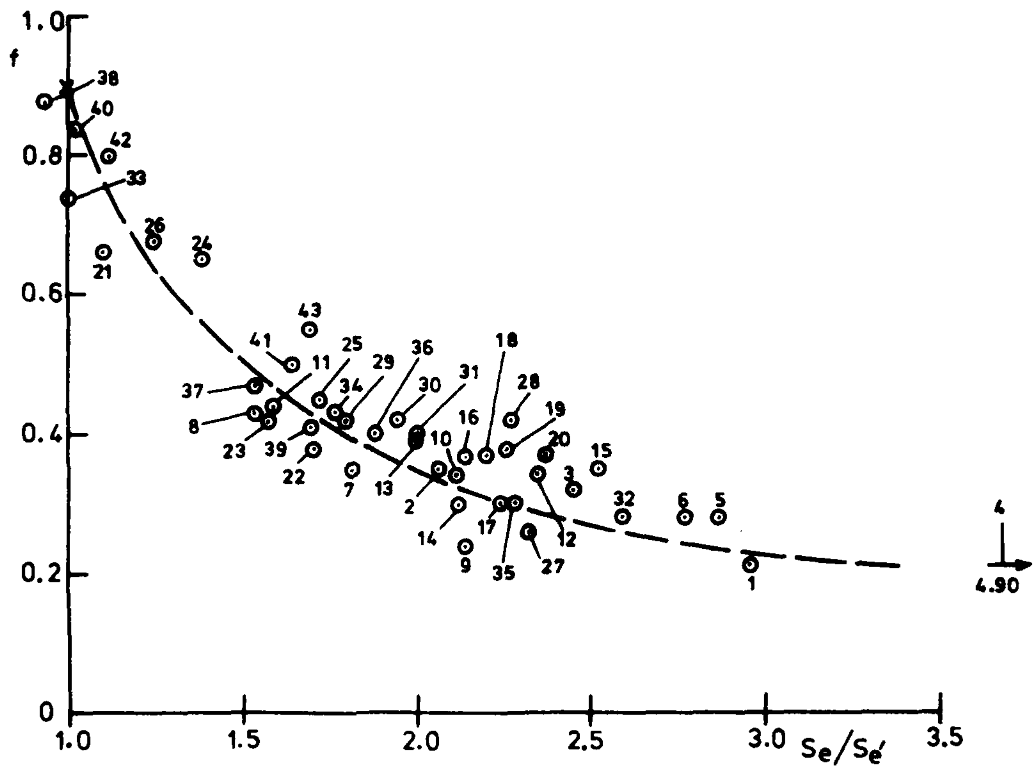


Fig. 16 Brake numbers measured with BV-11 (low pressure tyre) vs. relative brake distance of aircraft Douglas DC-9-21.

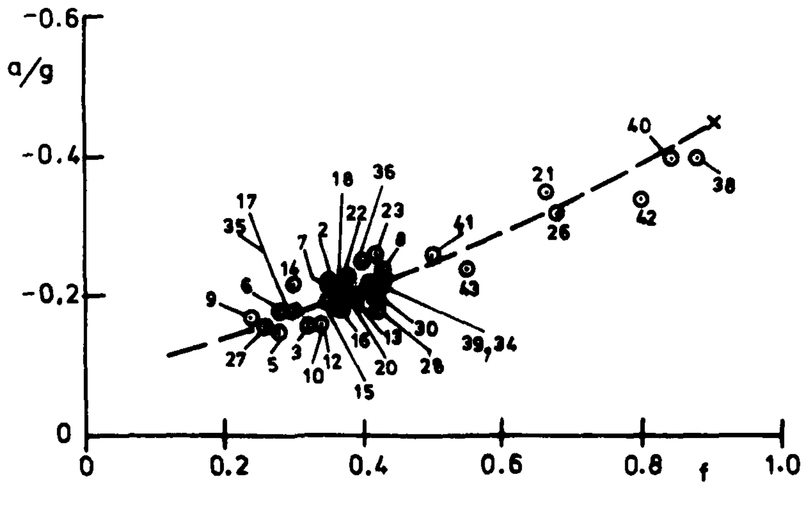


Fig. 17 Aircraft DC-9-21 deceleration vs. BV-11 measured brake numbers.

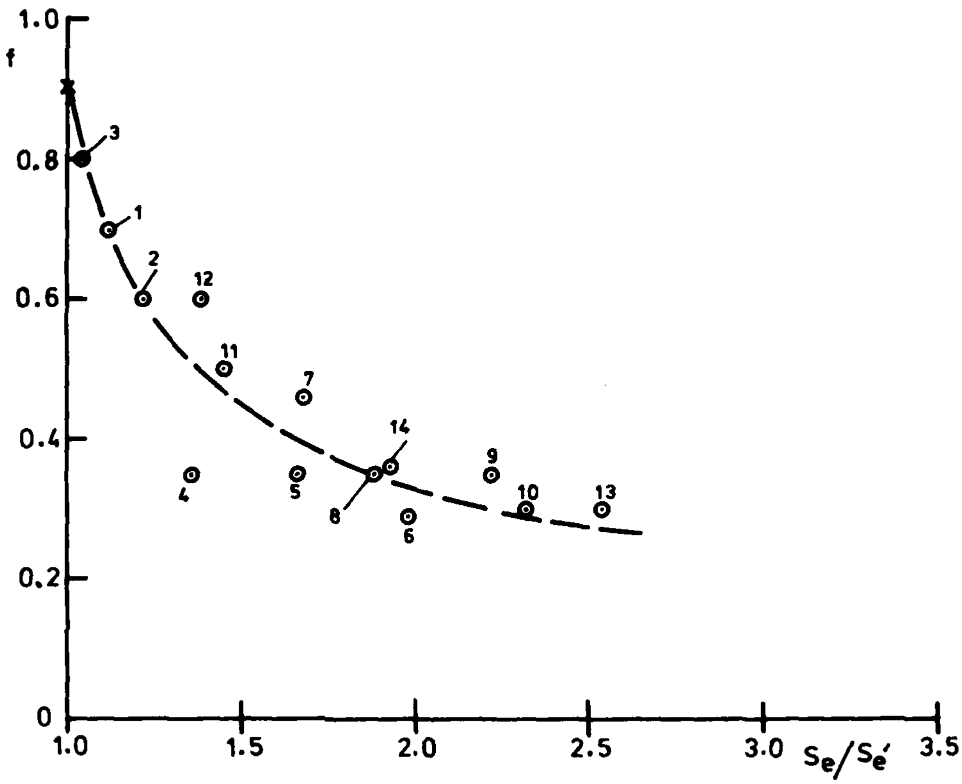


Fig. 18 Brake numbers measured with BV-11 (low pressure tyre) vs. relative brake distance of aircraft Boeing 737.

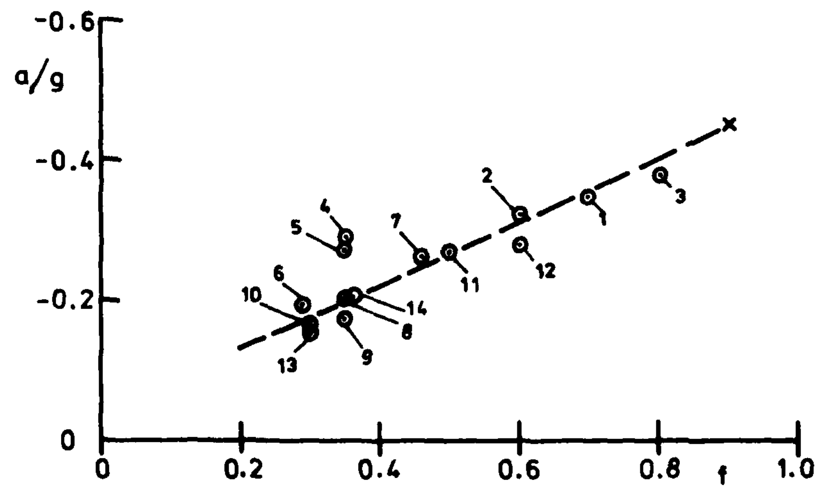


Fig. 19 Aircraft B-737 deceleration vs. BV-11 measured brake numbers.

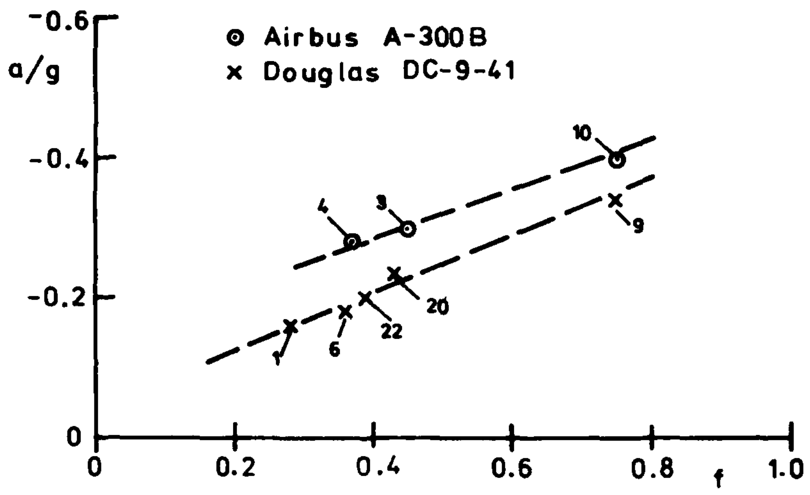


Fig. 20 Aircraft deceleration vs. Friction Tester (high pressure tyre) measured brake numbers.

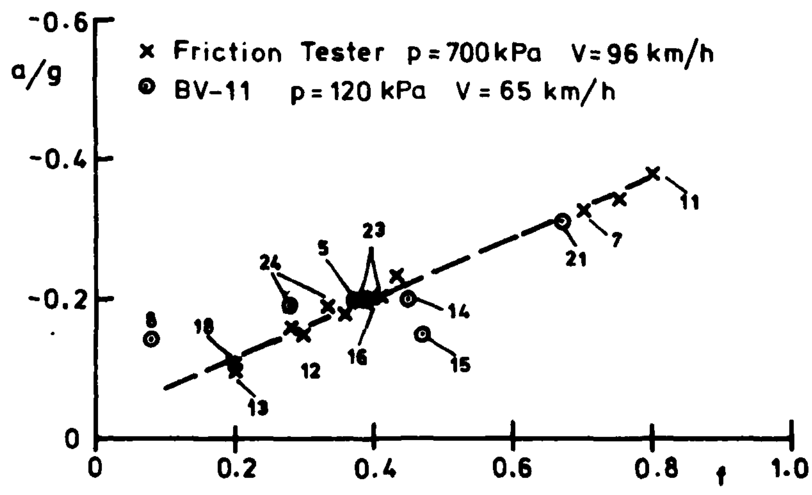


Fig. 21 Aircraft DC-9-41 deceleration vs. vehicle measured brake numbers.

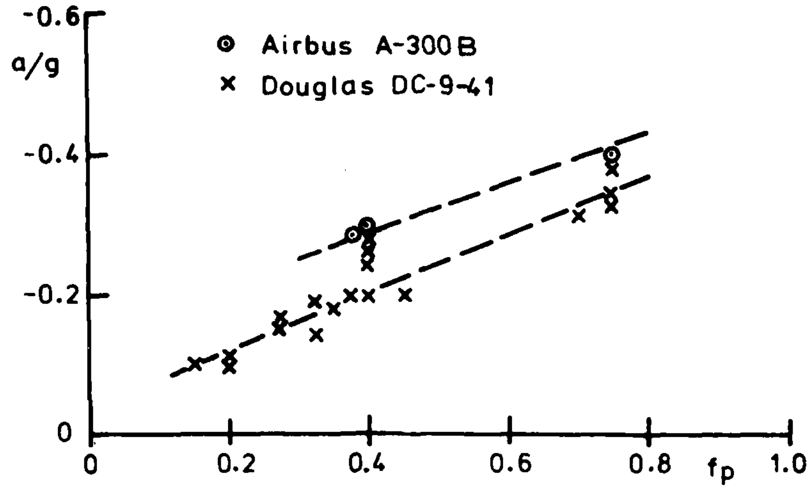


Fig. 22 Measured aircraft deceleration vs. pilot determined (brake distance from 50 to 0 kt) brake numbers.

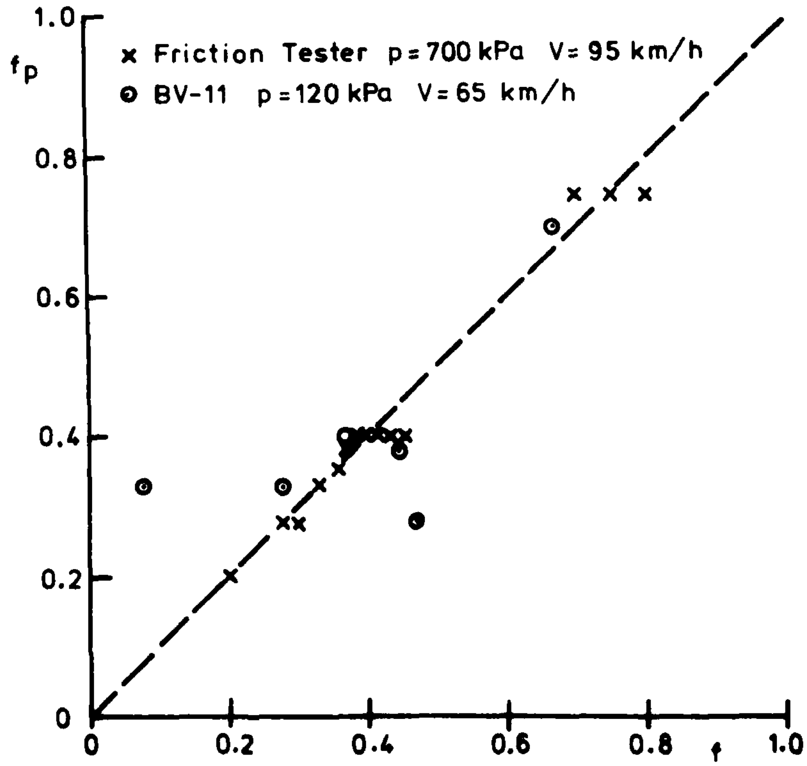


Fig. 23 Pilot determined (brake distance used from 50 to 0 kt) brake numbers vs. measured brake numbers.

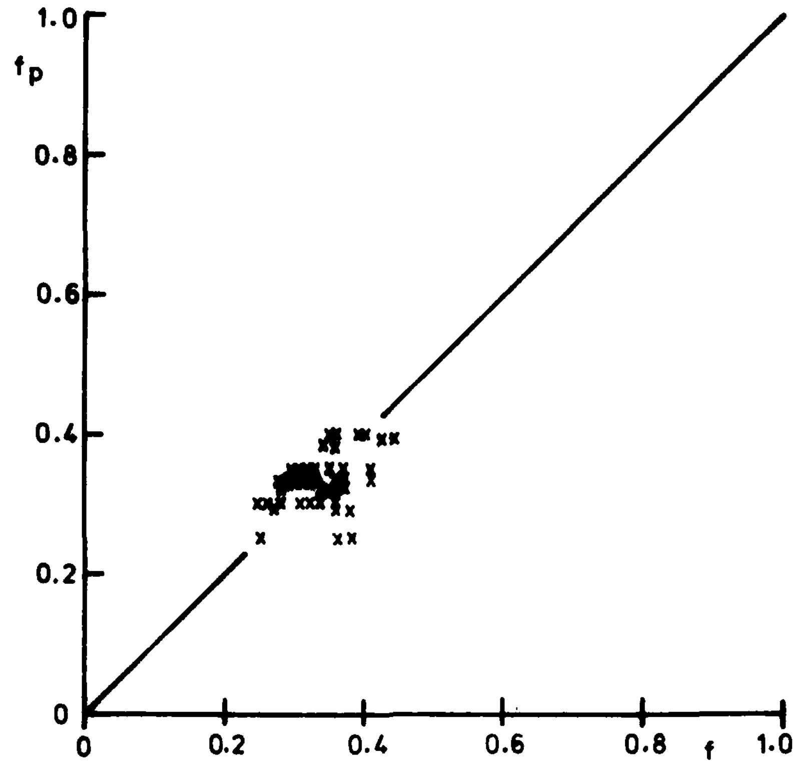


Fig. 24 Pilot determined (brake distance used from 50 to 0 kt) brake numbers vs. measured brake numbers (Friction Tester p=700 kPa V= 95 km/h.

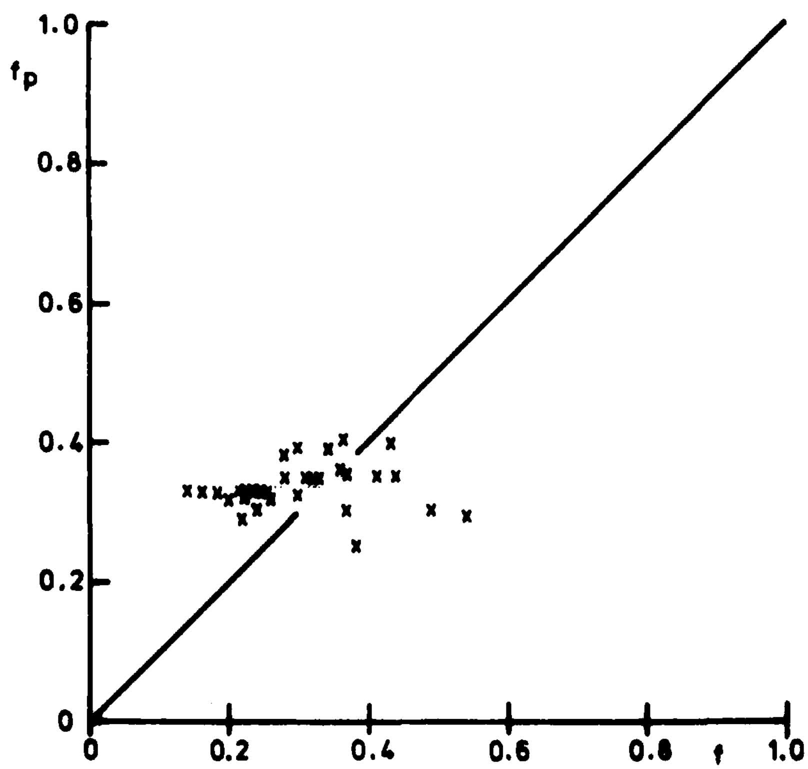


Fig. 25 Pilot determined (brake distance used from 50 to 0 kt) brake numbers vs. measured brake numbers (BV-11 p = 120 kPa V = 65 km/h).

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